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Chapter 13

Synchrotron Based Techniques in Soil Analysis: A Modern Approach

Surabhi Hota

Abstract

Soil is a highly heterogenous system where a number of physical, chemical and biological processes are taking place. The study of these processes requires analytical techniques. The electromagnetic radiations in the form spectroscopy, X-Ray diffraction, magnetic resonance etc. have been used in the field of soil analysis since decades. The study of soil nutrients, mineralogy, organic matter and complex compounds in soils use these techniques and are successful tools till date. But these come with a limitation of lesser spatial and spectral resolution, time consuming sample preparation and destructive methods of study which are mostly ex-situ. In contrast to the conventional spectroscopic techniques, the synchrotron facility is of high precision and enables non-destructive study of the samples to a nano scale. The technique uses the high intensity synchrotron radiation which is produced in a special facility, where the electrons are ejected using very high voltage and accelerated in changing magnetic field, at a speed of light resulting in a very bright radiation that enables a very précised study of the subject. For example, in studying the dynamics of P and N in soils, SR aided XAS are used to study the K-edge spectra of these nutrients, without any matrix interference, which used to be a problem in conventional SEM, IR or NMR spectroscopy. These radiations provide high energy in GeV, which imparts high sensitivity and nanoscale detection. Basically, the SR facility improves the precision of the existing spectroscopic techniques. This chapter discusses how the Synchrotron radiations aid to improve precision in various field of soil analysis such as, carbon chemistry, nutrient dynamics, heavy metal and contaminant speciation and rhizosphere study. However, the technique also come with major limitations of requirement of very high skill for preparation of samples, inadequate availability of references for studies related to absorption spectrum and control of radiation damage. Applications and limitations of the technique thoroughly reviewed in this chapter with an aim to provide a brief idea of this new dimension of soil analysis.

Keywords: Soil, Synchrotron, analysis, energy, resolution

1. Introduction

Soil is a heterogenous system and habitat for numerous flora and fauna, where umpteen chemical, physical and biological processes are operating to make it a living system. These processes are, element mineralization and immobilization, redox reactions, decomposition of organic matters by microbes, movement of nutrient elements towards the plant roots and related soil water movements, the complex processes near the rhizosphere, accumulation and distribution of elements and their chemical transformations in to different complexes and valency, weathering of rocks and minerals to form soil and related soil forming processes. To understand these processes, several techniques have been developed and experimented by the soil researchers from time to time. And there are numerous remarkable techniques that have aided to the human understanding of complex matters. Most of these techniques use source of energy and illumination for quantification of the elements and studying the complex structure of a system. Such techniques are Diffraction/scattering for crystallography; Polarimetry for measuring the shape of complex molecules and the properties of magnetic materials; Imaging for highly detailed imaging of small animals, and ultimately humans, to the substructure level of biological and physical material, using light from infrared to hard X-rays; Spectroscopy for analysis of chemical compositions and speciation of elements [1]. However, these techniques have several limitations in terms of their sensitivity, spatial resolution, lengthy sample preparation procedures and most of them are dependent upon destructive sampling and ex-situ analysis. With the development of synchrotron facility around the world, the exploitation and study of these processes have been made possible to the molecular level and in-situ because of the unique qualities of a synchrotron radiation viz.; high brightness, wide energy spectrum, highly polarized radiation and time structured emission. This gives the SR an advantage of due to high proton flux, possibility of beam tunability and weak scattering, high sensitivity resulted from acceleration of heavy ion beams to high energy.

Synchrotron Radiation (SR) is basically an electromagnetic radiation which is emitted when the charged particles are radially accelerated. Natural synchrotron radiation (SR) is as old as the stars produced due to charged particles spiraling around magnetic field lines in space [2], while short-wavelength synchrotron radiation generated artificially by in circular acceleration of relativistic electrons only ways back to early nineties [3, 4]. The synchrotron principle was invented by Vladimir Veksler in 1944 [5]. Edwin McMillan constructed the first electron synchrotron in 1945 [6]. The first ever synchrotron was successfully made in 1947 under the direction of Herbert Pollock at General Electric Research Laboratory, NY. And the first synchrotron radiation was observed by Floyd Haber on 24th April, 1947. This was a remarkable achievement in the field of physics which today has led to large, full-fledged synchrotron facilities around the world. The first-generation synchrotron facilities were only being used to study the fundamental properties of matter and was more of a particle accelerator [2]. Presently, the synchrotron facilities have upgraded to third generation, which enable the use of low energy or soft and high energy or hard X-rays, UV and longer wavelengths. The first ever third-generation hard X-ray source was European Synchrotron Radiation Facility (ESRF) in Grenoble followed by the Advanced Photon Source (APS) at Argonne National Laboratory with an energy of 7 GeV. The synchrotron is one of the first accelerator concepts to operate as large-scale facilities, where bending, beam focusing and acceleration could be separated into different components and where the magnetic field is guided in a time dependent manner, to synchronize with a particle beam of increasing kinetic energy.

There are more than 50 facilities in operation worldwide (http://www.lightsources.org) and are being used by more than 15,000 researchers. Some large facilities are listed in **Table 1**. There are a few large synchrotron facilities that have been operating with high electron energies, as high as 8 GeV (SPring-8 in Harima Science Garden City in Japan). PETRA III, which took up operation in 2009, is the most brilliant storage-ring-based X-ray radiation source in the world. As the most powerful light source of its kind (https://petra3.desy.de/ index _eng.html). These machines are physically large (850 to 1,440 m in circumference) with a capability for 40 or more beamlines. There is are also many smaller facilities (120 to 280 m in circumference) which have come in to existence in recent past, having lower electron energies (from 1.3 to 3 GeV). There are also some fourth-generation synchrotron facilities which have been conceptualized by few countries recently.

S.No.	Name of facility	Country	Energy (GeV)	Circumference (m)	Year of Operation
	Indus II	India	2.5	173	2005
1	National Synchrotron Light Source (NSLS-II)	US	3	792	2015
2	PETRA III	Germany	6	2304	2009
4	SPring-8	Japan	8	1436	1997
5	Advanced Photon Source (APS)	US	7	1104	1995
6	Progetto Utilizzazione Lucedi Sincrotrone (PULS)	Italy	1.5	33.5	1980
7	Canadian light source	Canada	2.9	147	2004
8	Australian Synchrotron	Australia	3	216	2006
9	Shanghai Synchrotron Radiation Facility	China	3.5	432	2007
10	ALBA	Spain	3	270	2010
11	Sirius	Brazil	3	518.2	2018
12	Pohang Light Source II	South Korea	3	281.82	2011
13	Swiss Light Source	Switzerland	2.4	288	2001
14	European Synchrotron Radiation Facility	France	6	844	1992
15	Kurchatov Synchrotron	Russia	2.5	124	1999

Table 1.
Synchrotron facilities around the world.

Synchrotron facilities can generate frequencies over entire range of the electromagnetic spectrum. In addition to having a high intensity, the synchrotron light has other properties useful to researchers. Wavelengths produced by SR, may range from 10 to 11 m hard X-rays) to 106 m (infrared light), emitted in short pulses (~100 ps wide spaced at 2 ns), partially coherent and arrives in parallel rays, highly polarized, isolation of specific wavelengths are possible with the use of diffraction or crystal gratings. And most importantly, light is released as a very narrow cone [7] which is then focused to provide a very narrow beam at the work station.

There are a number of techniques that have been used by the researchers for study of soils, they are: STXM- Scanning Transmission X-ray Microscopy, NEXAFS- Near Edge X-ray Absorption Fine Structure Spectroscopy, FTIR- Fourier Transform InfraRed Spectroscopy, μXRD- Micro X-ray Diffraction, EELS- Electron Energy Loss Structure spectroscopy, EXAFS- Extended Absorption Fine Structure Spectroscopy, XANES- X-Ray Absorption Near Edge Structure Spectroscopy [8], HRTEM-High Resolution Transmission Electron Microscopy, SXRF- Synchrotron Based X-ray Radiation Fluorescence, XFS- X-ray fluorescence spectroscopy, X-ray µ-computed tomography [9–11], SEM- Scanning Electron Microscopy, TEM-Transmission Electron Microscopy.

These synchrotron-based techniques have proved to increase the precision of determination of many soil parameters such as carbon chemistry of soil [12, 13], rhizosphere nutrient transport and other mechanisms [14, 15], heavy metal quantification and remediation, microbe-metal interaction mineral transformation, study of physical parameters of soil, soil fertility study.

Methodology: This chapter reviews the works done in the field of soil analysis for physical, chemical and biological parameters, using SR facility, all over the world and how it has aided to the improvement in precision and accuracy of the study.

2. Components and working of a synchrotron facility

A synchrotron facility in general, consists of:

1. Electron gun: It consists of a transformer which feeds a very high voltage (in hundred thousand Volts, approximately, 200000 V of DC) of electricity through a cathode which causes the electrons to jump off the surface. The cathode is made of tungsten-oxide disk, otherwise called a button. As electricity flows through the disk, the disk gets heated to about 1000° C, the temperature at which the electrons are released. A screen near the button is given a short, strong positive charge 125 times per second, which pulls the negative charge particles, the electrons, away from the disk.

2. Linear Accelerator (LINAC): The electron ejected from the electron gun, are fed into the LINAC. The energy of acceleration is provided by the Microwave radio frequency fields to accelerate the electrons to the speed of light. The speed of the electrons reaches approximately to 3 x 108 m/s. The LINAC produces electron pulses in a duration of approximately up to 132 nano seconds (ns). The electrons which become the photos now, must travel in a vacuum to avoid hinderance and reduction in velocity by colliding with other atoms and molecules. The vacuum chamber pressure is kept around 10–11 torr.

3. Booster Ring: The electrons circulate in the booster ring, to get a boost in energy from approximately 250 MeV (Mega electron volt) to approximately 2.9 to 6 GeV by the radio frequency cavity generated microwaves. The Booster Ring increases the speed of the electrons close to the speed of light (approximately 99.9999985 percent of the speed of light). There are two types of electro magnets in the booster ring. These magnets create the magnetic field, which is used by the synchrotron to guide the electrons around the booster ring. The magnetic field of the quadruple magnets are used to force the bunches of electrons into a fine beam within the vacuum chamber.

4. Storage Ring: After the electrons have gained sufficient energy to produce light, the injection system transfers them from the booster ring to the storage ring. The process of transferring electrons from booster to storage ring occurs approximately once per second up to 600 cycles which may take about 10 minutes. Once entered the storage ring, the electrons keep circulating for four to twelve hours and every time the dipole magnets/bending magnets bend the path of electron flow, photons are released. The bending magnets are aimed to circulate the electrons in a circular path [16]. After each turn of the bending

magnets, there is a photon port to allow the light to travel down the beam lines to the research stations.

5. Beam line: Each beam line consists of an optics cabin, experimental cabin, and control cabin. The optics cabin has optical instruments used to extract the type of radiation required for the experiment. The experimental cabin is for support mechanism, and provides environment for the sample study. Instruments called detectors record the information generated from the sample are recorded by the detectors. The control cabin, as the name suggest, allows the researchers to control the experiments and collect the data.

6. End Station: The final result is obtained at the end station. The components of end station are experiment specific. There is an optic hutch, consisting of mirrors by which the selected wavelengths of synchrotron light are focused onto the sample in an end station. The samples are placed in the experimental hutch, which consists of a sample holder and a detection system, specific to the technique adopted by the researcher. Also, includes computers through which the experiment is controlled by the researcher.

3. Organic carbon chemistry in soils observed by synchrotron based spectroscopy

Soil is believed to be the largest pool of terrestrial organic carbon containing about 1500 Pg C which is higher than the atmospheric and biotic pools combined [17, 18]. Organic C is crucial in maintaining the balance of inorganic form, specially, CO_2 in the atmosphere, which in turn, controls the global climate scenario [19]. The entire carbon cycle revolves around the organic C fraction. The decomposition of organic matter, from animal and plant residues and subsequent humification, leads to the formation of complex organic compound leading to significant structural and composition changes [20]. Organic compounds released from animals, plants, microbial cells, have a range of size and complexity from monomers to mixtures of biopolymers. This complexity makes chemistry of soil organic matters difficult to study. Organic C shows very high chemical and spatial complexity, creating significant analytical problems in the existing methods [21–24]. Soils characteristically have low amounts of C as compared to pure biological samples. They require relatively higher energy to substantially improve the detection limits and data that allow better quantification of C chemistry. The existing techniques are mostly destructive, or the samples are processed ex-situ, for analysis. This sometimes causes the loss of delicate structure of the complex organic matter. SR based spectroscopic techniques have proven to be an advanced tool to study the organic C chemistry of soils, as it enables the non- destructive micro and nano-scale analysis and enables keen study of reactivity, composition, heterogeneity, physical site of organic materials, and mineral-organic matter interactions. The high energy of SR provides very high spatial and spectral resolution.

SR-based scanning transmission Fourier transform infrared (FTIR) spectroscopy, X-ray microscopy (STXM) and C (1 s) near-edge X-ray absorption fine structure (NEXAFS), have proven to be unique and non-invasive in studying the complex processes of C chemistry in soils, in the recent past. These techniques have been used to reveal the Spatial organization of C forms in microstructures, functional group chemistry of C, interaction of C with soil matrix, surface Interactions of organic C and minerals.

The identification of the compound structure of the SOC and DOC involves basically, identifying the type of chemical bonds and functional groups in a molecule. And because of complex nature of the spectrum produced by the organic compounds, the identification and differentiation of the bond become difficult with low energy, conventional spectroscopic techniques. At low spectral resolution, the peaks seem to be overlapping and the fingerprinting becomes only partially useful. This limitation has been overcome by the incorporation of SR in to the spectroscopic techniques. The identification of the structural characteristics with high precision has become possible and even the study of impact of management on SOC cycle and composition could be successfully carried out by aid of SR based techniques in various studies [13, 23, 25–32].

The aided advantage of SR is its brightness, which can be defined as the photon flux or power emitted per source area and solid angle, is 100–1000 times greater than the brightness obtained from a conventional source [33, 34]. FTIR spectroscopy has been considered the most powerful technique for identifying types of chemical bonds and functional groups in a molecule which produces IR absorption spectrum, in the form similar to fingerprint. FTIR combined with microscopy allows probing of small areas in shorter time intervals and with an optimum signal-to-noise ratios. However, SR-FTIR spectroscopy could reveal the quantity, structure composition, and distribution of chemical constituents in humus fractions [13, 23]. In some studies, it has also been used to identify stable soil aggregates and black C particles chemistry [27, 35] and these studies show that, the SR-FTIR spectra has stronger band width compared to conventional FTIR. Studies revealed that, FTIR spectra below 1450 cm-1 normally leads to overlapping bands of indefinite quantity. SR-FTIR has a spectrum ranging from 4000 to 400 cm^{-1} and could measure the molecular level vibration of organic and inorganic functional groups [36, 37]. SR-FTIR can also identify the changes in intensities and vibrational characteristics of bands, shifts in frequencies and shapes of a particular band [38]. These properties have been exploited to study the molecular level changes in SOM composition due to management practices [13, 23, 39]. it was also made possible by this technique to study organo-mineral assemblages [27, 35].

NEXAFS is also such a technique which is being used by many researchers for similar studies in recent past. It is highly element-specific as the different elements show X-ray absorption peaks at different energies [40]. NEXAFS when combined to STXM, information as précised as 30–50 nm spatial resolution could be obtained. This technique is termed as NEXAFS spectromicroscopy. This technique has been used in study of humic fractions mined from highly complex soil matrices [13, 23, 24, 29, 41, 42], study nanostructures of polymers [43] and fingerprinting of C in biological materials [44, 45].

The results obtained from the SR-based techniques are basically an improvement over the pre-existing spectroscopic techniques, where the bond stretch (eg. C-O or O-H), π and σ transitions [23] are taken as the reference for speciation of the C containing species. However, the spectral signatures, or fingerprints of pure biological materials obtained from SR based spectroscopy can serve as a reference for interpretation of the results obtained from conventional spectroscopy. The results can then be quantified using chemometrical methods, multivariate analysis, regression modeling, principal component analysis or predictive modeling [27, 46]. In laboratory analysis of samples, chemical analysis of C samples can only provide the total OC, or different pools of C or fractions of humus, which are mostly quantitative. But the SR based techniques can reveal what is the actual composition of the TOC fraction or humus fraction. These revelations can be related to the stage of weathering of a soil, its pedogenesis and can also correlate the data to predict the responsible chemical, physical and biological processes. Information related to fingerprints of organic compounds such as proteins, nucleic acids, carbohydrates and lipids, predictive models and algorithms can be developed, which can be used by researchers with basic facilities, to predict the organic C chemistry and related processes. However, the data from fingerprints of standard substances is still inadequate to fully identify functional group chemistry for soil organic C and a strenuous effort is required to fill that breach.

4. Synchrotron based techniques in elemental speciation in soils

Soil is a very heterogenous system and the chemical and biological processes happening inside it are even more complex. The important processes, as mentioned in the introductory section, are dependent upon the concentration of different elements involved in process, their distribution and their chemical behavior, which makes their speciation very much crucial. Also, the speciation of environmental contaminants such as heavy metals are important as they lead to degradation of soils [47, 48]. XAS is a powerful technique to provide answer to questions related to the chemistry of an element present in ant system starting from minerals, to biological specimens and solutions [49–52]. The XAS technique basically scans the object of study using a range of X-ray energies. Hence, with the advent of synchrotron, the energy of X-ray could be increased. XANES and EXAFS are the two techniques XAS techniques which have been used in many studies for studying the elements in heterogenous environments, by selecting appropriate energies of the incoming X-ray photon with the aid of SR facilities and thereby generating chemical maps of an element in relation to its oxidation state and chemical bonding [53]. K-edge XANES has been used to test the speciation of Al on the thin surface coatings of quartz and feldspar grains in a loess soil [54], and studying the coordination of Al in imogolite and allophones [55].

X-ray techniques such as low-energy XRF (LEXRF) has been used to quantify Al in plant tissues to determine the toxicity levels. A study was carried out to determine Al accumulation in tea plants, in the soils with high acidity, resulted to high concentration of Al. it revealed that Al accumulated mainly within the cell walls of the leaf epidermal cells, also confirming that the apoplast are the tolerance mechanism of toxicity in tea plants because of results showing Al accumulation in apoplast and traces in symplast. Similar study in soybean showed higher accumulation of Al in roots [56] using LEXRF. Cr speciation has been done by using EXAFS in soils contaminated by leather tanning, reporting the dominant form as Cr (III) with low levels of Cr (VI) [57]. Different industrially contaminated soils have been studied for determination of and speciation of Cr using this technique [58, 59]. XANES has been used to identify associations of metals in contaminated environments. Fandeur et al. [60] reported that Cr (VI) was found in closed association with Mn-oxides concluding the role of Mn-oxides in oxidation of Cr (III) to Cr (VI). Jacobson et al. [61] reported Cu to be present in hotspots that are associated with organic matter within the soil matrix using in-situ XANES. Similarly, a study by [62], revealed the Cu hotspots not to be associated with calcium (Ca) carbonates, Fe oxides, or Cu sulfates. EXAFS has been used for speciation of As, based on the absorption spectra of As-O distances. Grafe et al. [63] used m-XRF and m-XAS to study the speciation of As in a chromated copper-arsenate (CCA) contaminated soil to determine the effects of co-contaminating metal cations (Cu, Zn, Cr) on As speciation. X-ray computed μ-tomography (SR-μCT) is also a powerful technique that enables study of internal structure and composition of sample without sectioning it physically. Other advantage over conventional technique is enables a 3D study of the subject. 2D study of the samples limit the projection of metals present in the sample, only in the direction of beam. SR-μCT has higher sensitivity, resolution and speed. SR-XRF is also a powerful technique devised to study the elements in environment. It has a very précised detection limit for many elements (<0.01 ppm).

5. Synchrotron based techniques in study of mineral structure, their occurrence and abundance in soils

It is known that X-ray diffraction (XRD) is a basic technique which has been used widely for the characterization and identification of crystalline structure of minerals. But it comes with some imitations like it cannot be used to study amorphous minerals, the slide preparation procedures are very much time consuming, requires invasive sampling. Also, the low energy and low flux make the diffractometer geometry very limited. The use of diffracted X-rays, instead of transmitted X-rays restricts the analysis of hydrated and oxygen samples. Compared to the conventional technique, the SR-XRD provides very high sensitivity due to energy tunable nature and high flux. It enables the non-invasive study of trace matters, amorphous minerals, hydrated and oxygen samples, thin films and solution phase. The study of areas as small as 1 mm^2 can be done with a beam spatial resolutions of <5 mm.

synchrotron-based techniques of XRD and XAFS, have greatly improved the understanding about the structural and chemical properties of amorphous minerals, such as iron oxide minerals like lepidocrocite, goethite and hematite. Their transformations of metastable phases to stable phases of iron oxides [64] and chemical reactions occurring on their surfaces have also been possible to study with the aid of these techniques., and chemical reactions occurring on their surfaces. [65] used XANES spectroscopy for identification and quantification of iron compounds in soils. Massive improvements have been achieved in understanding the structure of poorly crystalline and nanosized iron oxides species like ferrihydrite, by synchrotron XRD, EXAFS, and total X-ray scattering data. Studies also have used laboratory XRD to determine changes in the structural properties of goethite and hematite due to substitution by Al^{3+} than Fe^{3+} in mineral structure (up to 33 mol.%). Atomistic and long-range scales data regarding substitution of trace to low amounts of other elements in the structure of iron oxides on the basis of indirect, dissolution data have been predicted using synchrotron XRD and EXAFS [66–70]. The valence state of substituent elements, coordination states and their effects on element substitution in iron oxides nave been revealed by XANES spectroscopy [66].

6. Synchrotron based techniques in study of microbial interactions with contaminants/pollutants in the soil

SR-FTIR spectromicroscopy is a powerful technique which has come in to use in recent years for study of microbial activities with high spatial resolution to μm scale and temporal resolution to seconds scale, enabling keen study of processes at cellular level [71]. It combines three techniques viz.; microscopy, mid IR spectroscopy and SR based light source, which makes it possible to precisely locate the target, obtain its vibrational spectra and obtain very high signal to noise ratio.

Earlier FTIR spectromicroscopy technique used an aperture to take reading of smaller areas within the sample, because to take reading, one had to adjust the incoming light to either eliminate some part of it or to distribute it among detectors, uniformly. This resulted to reduction in signal strength. The thermal emission sources are limited to focus an area of 75–100 mm in diameter only. In contrast to these conventional sources, a synchrotron infrared source can obtain spectra from smaller target areas without using aperture [72]. In SR-FTIR Spectro microscopy, one can use the infrared beam to visualize a spot as small as the diameter of its wavelength resulting to 0.7 times of spatial resolution [73–75].

The study of action of microbes over a geological surface (here, soil) is based on the fact that, the changes carried out by microbial action (mineralization, immobilization, biodegradation) is monitored by the study of the vibrational spectra of the substrate (heavy metal or pollutant). Many studies have been carried out to find out the reference spectra of several contaminants such as, Chromium and molybdenum hexacarbonyls [76], Pentacyanonitrosyl-complexes of chromium and molybdenum [77], Aromatic chromium tricarbonyls [78], Explosive molecule vapors [79], polycyclic aromatic hydrocarbons (PAH) [80–83], Fluoranthene and benzofluoranthenes [84], Organo-arsenic (III), –antimony (III) and -bismuth (III) thiolates [85], PAHs incorporating the peropyrene structure [86], Nonregular PAHs [87], large PAHs [88] Naphthalene and anthracene [89], 1-nitropyrene [72] Toluene-.

3,4-dithiolatoantimony (III) derivatives [90], Trimethylarsine oxide [91] phosphorus tricyanide [92] Oil spill [93] Quinoline and Phenanthridine in Solid Argon and H2O [94] 6-nitrochrysene [95, 96] Arsenate on Fe-Ce bimetal oxide [97].

A general step-by-step scheme of studying the microbe interaction is given as follows:

Visual examination of the specimen surface under stereoscope to study the overall morology and topography.

↓

Application of sterile liquid to keep the surface microbes alive during study.

↓

Removal of uneven fragments over the surface to prevent hinderance in scattering using mini hammer.

↓

Cleaning of specimen surface by sonification and UV-radiation sterilization.

↓

Specimen placed inside the sterile chamber of microscope and identification of surface to be studied.

↓

Microscopic volume of sample collected from field or microbial culture on to the specimen surface selected.

↓

Coupling FTIR-spectroscopic system to SR light source.

↓

Recording of vibrational spectrum of target sample.

Apart from the above-mentioned organic contaminants, metal contaminants speciation and bioavailability has also been widely determined using SR techniques. In a study [98] XAS was used to explore the short-term aging profile and the long-term speciation of dissolved Cu, CuO, and CuS nanoparticles, concluding that the short-term reactions with nanoparticles are dependent on the Cu form and soil chemistry, while the long-term reaction are independent of the form of Cu and transformed into iron oxyhydroxide or natural organic matter bound Cu. Similarly, Colzato et al. [99] used Cadmium L-edge XANES to study short-term temporal changes in Cd speciation and long-term changes in Cd extractability to conclude that highly weathered Oxisols and less weathered Entisols and Mollisols contain Cd bound to organic matter and Fe and Al oxides. Mariet et al. [100] used EXAFS to study a century old Pb leftover from metallurgical activities and reported the presence of Pb mainly as sorbed to Fe oxy(hydr)oxides, which was a significant finding of great consequence to environment. SR based techniques have also been used recently to study real time biodegradation of organic chemicals [101], where it was predicted that humic acid accelerates the degradation of polyaromatic hydrocarbons (PAHs) by enhancing the solubility of the PAH, thereby increasing PAH bioavailability to microorganisms. SR-FTIR was used to study the effect of HA on the degradation kinetics of pyrene by Mycobacterium sp. on a magnetite surface [101].

7. Synchrotron based techniques in studying soil nutrient (nitrogen and phosphorus) dynamics

Phosphorus is a major essential nutrient to plants and directly involved in the metabolic activities of plants, maintain structural integrity and directly affecting the economic yield of crops due to its crucial role in fruit setting and flower development. P found in many forms in soil, organic or inorganic. The form of P in a soil decides its fate of mineralization, fixation, and availability as well as interaction with other compounds in soil. This makes the study of P speciation very much important. But low concentrations of P in chemical and organic species make it difficult to specify the form of occurrence of P due to matrix interferences [102, 103] using conventional techniques like SEM, IR spectroscopy and NMR spectroscopy.

But due to the aided advantages of SR-XAS, a matrix interference free data has been made possible. The technique uses XAS spectra for identification of the species. However, it represents the average of spectra of all the P species present, hence, model analogues of P species are used as reference to extract the individual spectra from the overall spectra. The conventional techniques involve the chemical processing of sample followed by colorimetric analysis, or other extractant methods, which mostly involves the removal of P from its natural environment (soil matrix or colloid) and resulting to possible alteration of original form of occurrence. However, use of SR techniques such as XANES and EXAFS have proved to be promising in soil P speciation. These techniques involve the study of spectrum produced by only one element (i.e., K-edge spectrum of P) of target irrespective of other elements present. Brandes et al. [104] have studied the phosphorus K-edge XANES spectra of potassium phosphate and various organic P species. The K-edge spectrum of P species in XANES can be identified by characteristic line feature, for example, a pre-white line feature indicated the PO_4 tetrahedra in coordination with a transition metal. Similarly, a weak pre-white line showing absorption peak at 2-5 eV indicated Fe (III) phosphate and adsorbed Phosphate on it [16]. Such features are very prominent for P minerals like phosphorsiderite and strengite [105]. Simlar studies have been carried out by few researchers till date, which uses XANES for speciation of Soil P [106–113]. XANES has been used to study adsorbed species of P on Fe and Al oxides [110].

N is also a major essential plant nutrient involved in structural integrity to metabolic activities of plants. The inorganic forms of N have been well explored and its analysis procedure in soil system is well established. But the nature of soil organic nitrogen (SON) has still remained relatively unexplored given its importance in the N cycle [114], as half of the SON have been termed as the unknown N [115]. The dissolved organic N (DON) also has the same fate as SON in terms of its characterization [116]. There are several methods that have been devised to characterize the SON fraction as hydrolysable N, NH3-N and unidentified N, such as, acid hydrolysis [117], pyrolysis, mass spectrometry and NMR spectroscopy [118, 119]. The use of X-ray spectroscopic methods in this field has come in to existence in recent past only [25, 120–124], which come with their obvious limitations of low energy, sensitivity and incapability to determine very small fraction of samples and limited number of reference spectra.

As mentioned in the previous regarding P determination, XANES K-edge N spectra has been used in few recent studies for speciation of SON and DON, which are present in very low concentrations, due to their highly sensitive beamline characteristics. And these works have been focusses in the direction of developing appropriate N reference standards [125]. The N K-edge XANES requires very high flux beamline critical of the study subject, and it occurs at photon energy of around 400 eV. An N-XANES represents the average of spectra of all the N species present, hence, reference spectrum of N species is used to extract the individual spectra from the overall spectra. This is almost like a fingerprinting technique where reference spectra and resultant K-edge spectra are compared to conclude the speciation. The peak resonance spectra of ammonium compounds were found to be around 401 eV [126], for KNO3 and Ca (NO3)2 it is around 412 eV, pyridine-based compounds at 398.7 eV. N-XANES has been used to characterize Maillard reaction-produced humic substances in DOM-related geomaterials [122], to study the aquatic sediment humic acids and their characterization to pyridines and oxidized pyridines [123]. These approaches had the major disadvantages of physical alteration and poor correlation between soil properties and chemical characteristics of extracts [125]. Because organic N fraction is closely associated with the clay size fractions of soil, the analytical technique that did not involve much chemical alteration, came in to popularity in the recent years, with the advent of SR based XANES. N-XANES has been used to study the dynamics of N-compounds in the rhizosphere of field pea (Pisum sativa L.) [127], characterizing heterocyclic (pyridinic) N in pyridines, pyrazines, nitrilic-N, $-N^{1/4}$, amide N and –NH– and nitroaromatic-N. N K-edge XANES was used to derive the spectra of soil to study the changes in SON compound by changes in pedoclimatic properties and cultivation duration [128].

8. Synchrotron based techniques in soil rhizosphere studies

Soil rhizosphere is a very complex yet important part of soil–plant root interaction. The microbes inhabiting the rhizosphere, the root exudates from plants, their interactions with each other and with the surrounding environment is crucial for nutrient cycling, nutrient release from SOM and ultimately plant growth. However, the study of rhizosphere has not been easy due to its complexity. The very fine root structures are not easily identifiable with existing techniques. The visualization of complex processes taking place in the rhizosphere require very high intensity beam as well as nanoscale spatial resolution, which have been met recently by some interventions which use SR for study.

STXM has been used to investigate the rhizosphere in few recent studies, for studying OC distribution within bacterial biofilms at fine scale [129–131] soil microaggregates [12, 26, 51] and bacteria-soil mineral interfaces [132]. Along with STXM, NEXAFS has been used to study oxidative damage of lignocellulosic materials [133] in bleaching and if such technique could be used in soil, it may help in quantifying the degradation of plant cells [134]. Synchrotron -IR microscopy (SIRM) is such a technique which has enabled the non-invasive mapping of root zone by using mid-IR spectroscopic signature. For SIRM studies, seedlings are sown in rhizoboxes, with modification of Lexan faces with windows such as Zn Selenide windows [135] and diamond window [136]. These windows allow direct observation of root-soil interface using SIRM.SIRM enables to focus the IR ton area as small as 6–10 mm [74, 75].

9. Limitations

SR based techniques have proven to be a boon in the field of soil analysis. However, it is still unexplored and there is a lot of scope for further research in this field. No technique is perfect and SR based techniques also come with several limitations. For example, μ- XRF uses hard X-ray beamlines for metal and metalloids with $Z > 20$, and at this beam line the lighter elements (N, P and S) cannot be studied. Similarly, soft X-ray cannot be used for heavy elements. The interpretation of data in K-edge XANES requires very much skill and accuracy, also when a specific element is being detected, there are chances of self-absorption leading to faulty interpretation. Also, the low energy of K-edge shell and low concentrations of the elements in soil pose limitations to this technique. Studies involving preparation of thin sections require very high skill. Detailed mapping of spatial distribution of organic C also poses challenges when information on single locations needs to be interpolated to processes encountered at the Pedon or landscape scale. Also, constraints such as sample preparation, control of radiation damage, or spectral quantification are faced in SR-FTIR studies. Other limitation of SR-FTIR is that it cannot be applied to all geological materials, because it is not possible to obtain IR-spectrum for those elements which are opaque at IR e.g., Iron oxides or sulfides and non-silica bearing minerals. The data from spectral information of standard substances is still insufficient to fully identify functional group chemistry for soil organic C and a concerted effort is required to fill that gap as soon as possible. However, these limitations also indicate the areas where the future research should be focused.

10. Future perspective

The SR based techniques are far more improved in terms of their accuracy compared to the pre-existing techniques that use EM radiation for chemical and physical analysis of soils. Soils are inseparable entity of agriculture production systems and environment as a whole. The advent of SR techniques has provided a better insight into the soil nutrient dynamics, organic C speciation, soil mineralogy, fate of trace elements, metal contaminants, organic pollutant bioavailability and microbial interactions. These results obtained from SR based techniques can be used to make significant predictions for sustainability of an agricultural system. For example, the forms of nutrient in a soil can indicate the underlying biogeochemical process which is occurring in real time and can be a good indicator of soil health. The correlation of the different forms with soil microbial flora and fauna will give insight into the health status of a soil. The forms of OC in soils are very good indicator of soil genesis, aggregate stability and capacity of a soil to provide nutrition for the microbial population. The clay coatings on the ped faces, cutans and other micromorphological features can be accurately visualized to understand the soil development processes and their stage of weathering, which in turn, decides the nutrient holding capacity, permeability, infiltration etc. and these are important parameters to decide cropping systems. The future researches should be focused towards overcoming the short falls of the techniques. For SR absorption techniques, a wide range of spectral libraries should be priority. The different techniques should be combined together to increase the array of analysis of the samples. In addition to this, significant constraints like need sample preparation, control of radiation damage and spectral quantification should be addressed.

11. Conclusion

The SR based techniques are remarkable improvement over the pre-existing spectroscopic techniques. The use of SR in soils is quite new and fairly unexplored dimension. Not a very less but also not a lot of research has been done towards analysis of soil parameters. The techniques such as XAS, FTIR and XRD have been widely used in soil studies, for soil nutrient dynamics, organic C speciation, soil mineralogy, fate of trace elements, metal contaminants, organic pollutant bioavailability and microbial interactions. The exploration of unexplored at nano scales has been possible with the advent of this technique. However, some limitations such as unavailability of adequate spectral references, converting the qualitative data in to quantifiable terms high skill requirements for handling and sample preparations and most importantly, the confinement of SR facilities to select places have restricted their wide adoption. Hence, future researches focused in this direction to popularize and further explore this technique to make it reachable in public domain.

Author details

Surabhi Hota
ICAR—National Bureau of Soil Survey and Land Use Planning, Regional Centre, Jorhat, Assam, India

*Address all correspondence to: surabhi.hota@gmail.com; surabhi.hota@icar.gov.in

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Plants adapt and develop their own mechanism to cope the environmental stress. The most effective means of combating environmental stress is the release and accumulation of plant growth-regulating hormones such as abscisic acid (ABA) and salicylic acid (SA). ABA, commonly known as stress hormone is released at the root tip in response to lower water potential, followed by its translocation to leaves where it alters osmotic pressure of the stomatal guard cells, leading to the closure of stomata openings to conserve moisture, thereby, preventing water loss via transpiration. Moreover, accumulated carbohydrates and amino acids being low molecular weight compounds play an active role in osmoregulation. SA, on the other hand, protects the plant against pathogenic attack [4].

PGPR/Treated Plant	Climatic stress	Alleviation of climatic stress
Bacillus cereu/Solanum lycopersicum	Heat stress	Increased production of exo-polysaccharide, cleavage of ACC-deaminase [9]
Bacillus amyloliquefaciens, Agrobacterium fabrum/Triticum aestivum	Water stress	Increase in biomass and grain yield [10]
Aneurinibacillus aneurinilyticus, Paenibacillus sp./Phaseolus vulgaris	Salinity stress	Facilitating ACC-deaminase activity, increased production of IAA, hydrogen cyanide and siderophore [11]
Stenotrophomonas maltophilia/Triticum aestivum	Salinity stress	Improved growth and yield, elevated antioxidative enzymatic activity, increased K^+ uptake [12]
Paenibacillus polymyxa/Brassica napus	Soil temperature	Production of antimicrobial and plant growth promoting volatile organic compounds (VOCs) [13]
Bacillus subtilis, Bacillus thuringiensis, Bacillus megaterium/Cicer arietinum	Climatically induced salinity stress	Regularized photosynthesis via assimilation of soluble sugars, chlorophyll and proline [14]

Table 1.
Alleviation of climatic stress via bioinoculants.

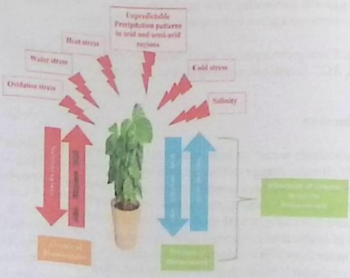

Figure 1.
Plant's responses to various stresses in presence and absence of bioinoculants.

Along with plant internal defense mechanism, the supportive role of PGPR has been widely acknowledged as an effective tool for sustaining plant growth and yield [5–7]. The plant root system serves as a habitat for numerous microorganisms that also interact with soil, thereby developing a complex ecosystem [8]. Certain PGPR inhabiting the rhizosphere penetrates roots and migrates through plant tissues; thereby impact the physiological and biochemical traits of plant cells (**Table 1**). This ecological aspect of the microbial community can be employed to strengthen the stress tolerance in plants, hence increasing their adaptation towards invincible climatic changes (**Figure 1**) [15].

The escalating demand and supply of chemical fertilizers and pesticides along with the persistence of their residual particles has posed an ultimate threat to humans as well as to the ecosystem. As an alternative, the acceptability of bio-fertilizers bearing bioinoculants has been increasing day by day. These bioinoculants act as a potential source of phytohormones which can rectify the climatic stress faced by plants. This chapter will explore various aspects of the utilization of bioinoculants for combating the climatic stress faced by plants.

2. Amelioration of heat stress via thermotolerant microbes

The major climatic stress faced by plants due to the rise in global temperature is heat stress which leads to water stress with counter effect on photosynthetic rate and flowering and fruiting in both tropical and sub-tropical crop systems [16]. The steady increase in surface temperatures is followed by an increase in soil temperature which can influence the root elongation process. Although, root elongation requires optimum soil temperature (specific to each plant), beyond which root elongation is stopped resulting in a stunted root system. Moreover, the activity of rhizobacteria is also relying on optimum soil temperature. In the forest ecosystem, N being a macronutrient acts as a growth-limiting factor. The flow of N cycling is deliberately subjected to temperature variation. The relatively increased temperature triggers N mineralization by microbes and thereby, prompting N uptake by plants as nitrates. However, in this process, the net nitrification is decreased [17]. The inoculation of PGPR is found to be more convenient than hsfs (heat stress transcription factors) genes, transgenic varieties, and breeding of heat-tolerant cultivators [18, 19].

Thermotolerance of certain PGPR has been evaluated to decrease the effect of heat stress on plants. The soybean plants inoculated with *Bacillus cereus* strain SA1 were exposed to heat stress for 5–10 days. The inoculated plants exhibited improved physiological (biomass) and biochemical (chlorophyll content and chlorophyll fluorescence) characteristics. Moreover, SA1 inoculation reduced the synthesis of abscisic acid and increased salicylic acid (a phenolic phytohormone involved in signaling and defense against pathogens) along with remarkable production of antioxidants (ascorbic acid peroxidase, superoxide dismutase, and glutathione) for sequestration of reactive oxygen species (ROS). A continuous increase in the synthesis and assimilation of Heat Shock Protein (HSP) was also claimed throughout the stress period of 5 to10 days, mainly due to the perpetual onset of GmHSP gene expression. Also, over gene expression of GmLAX3 and GmAKT2 were associated with enhanced potassium gradient and altered auxin and ABA stimuli (Aaqil et al. 2020). The bacterial strain *Bacillus cereus* capable of producing ACC-deaminase (0.76–C0.9 μM/mg protein/h) can cleavage ACC to α-ketobutyrate and ammonia to increase heat tolerance in tomato (*Solanum lycopersicum L.)*. Moreover, increase in synthesis of exopolysaccharide (0.66–C0.91 mg/mL) showed promising plant growth in tomato [9] (**Table 2**). Moreover, the presence of enzymatic antioxidants

Treated Plant/PGPR	Stress Alleviation Effect
Potato/*Paraburkholderia phytofirmans*	ACC deaminase production [20]
Tomato/Mycorrhizae	Reduction in lipid peroxidation and H_2O_2, higher ROS scavenging activity [21]
Bacillus amyloliquefaciens, Azospirillum brasilense Pantoea dispersa, Serratia marcescens, Pseudomonas spp.	ROS reduction, pre-activation of heat shock proteins [22]
	ACC deaminase production [23]
Apple and pear/*Ps. fluorescens*	Competition with INA+ bacteria [24]
Grapevine/*Paraburkholderia phytofirmans*	ACC deaminase production [25]
Soy/*Bacillus aryabhatthai*	ABA production [26]

Table 2.
Alleviation of heat stress via bioinoculants.

such as superoxide dismutase (SOD), peroxidase (POD) and catalase (CAT), and accumulation of metabolites such as amino acids and proline had boosted the scavenging activity against ROS under heat stress.

Among different agro-ecological zones, the arid and semi-arid regions are highly vulnerable to climatic changes mainly due to dynamical precipitation patterns. Being a staple cereal crop, the wheat and its associated endophytic and epiphytic bacterial diversity was investigated for thermotolerance at a temperature range of 30–40°C, pH 3–11, and 3–20% NaCl concentration [27]. Among 32 bacterial strains of 15 genera, 10 strains were reported to exhibit six different plant growth-promoting traits under heat stress. *Arthrobacter sp.* (66.0 ± 0.7 mg L^{-1}) possessed high solubilization of phosphorus followed by *Pseudomonas japonica* (64.6 ± 0.9 mgL^{-1}). Whereas, the potassium solubilization was highest for *Methylobacterium mesophilicum*. *Pseudomonas putida* exhibited the highest IAA production (70.8 ± 1.5 µg mg^{-1} protein day^{-1}) followed by *Rhodobacter capsulatus* (69.1 ± 0.5 µg mg^{-1} protein day^{-1}). The highest production of siderophore had been shown by *Alcaligenes faecalis* (4.9 ± 0.1 mm). Being thermotolerant, *Alcaligenes faecalis* and *Pseudomonas poae* were also characterized as alkali tolerant with 5% NaCl and 10% NaCl tolerance respectively. Besides the production of IAA, siderophore, and ammonia, these bacterial strains were also involved in the solubilization of phosphorus and zinc under heat stress. The chief bacterial groups characterized for nitrogen fixation at high temperatures were *Acromobacter*, *Alcaligenes*, *Bacillus*, *Delftia*, *Providencia*, *Pseudomonas*, *Rhodobacter*, and *Salmonella*.

Similarly, Sorghum being native to arid habitat was inoculated with a thermotolerant bacterial strain of *Psuedomonas aeruginosa* AKM-P6 which was isolated from the rhizosphere of Pigeon Pea plant grown under semi-arid conditions [28]. The inoculated Sorghum seedlings survived the temperature range of 47–50°C up to 15 days. The thermotolerance was imparted by the biosynthesis of high molecular weight proteins in leaves which protected cellular membranes from injury and improved metabolite production mainly proline, chlorophyll, sugars, amino acids, and proteins along with plant biomass. Another strain of *Pseudomonas sp.* PsJN was used to evaluate the heat-stress tolerance level in 18 clones of potatoes via both *in vitro* and *ex-vitro* inoculation [29]. The inoculated potato nodal cuttings were exposed to the temperature range of 20/15°C or 33/15°C day and night for six weeks. The increase in temperature had drastically affected the root system and tuber number and tuber fresh weight. An average root to shoot ratio decreased from 3.7 at 20/15°C to 1.7 at 33/15°C in non-inoculated plantlets and respectively, from 4.3

to 1.5 for inoculated ones. ABA deficient plantlets lack the tuber formation whereas tuberization in inoculated plantlets was significant at 33/15°C. As compared to in vitro, the ex-vitro performance of potato clones (LT-7) exhibited the effectiveness of rhizobacteria in colonizing certain potato clones under heat stress. Hence, the thermotolerant bacterial strains may serve as inoculants and bio-control agents for improving crop productivity with accelerating climatic temperature stress.

3. Amelioration of water stress via 1-aminocyclopropane-1-carboxylate deaminase/exopolysaccharide production

Due to the changes in minimum and maximum temperature, high water requirement and reduction in yield was observed in plants. Although the production of 'Ethylene' as plant stress hormone occurs in response to climatic stress encountered by plants; its accumulation in high amounts could be deleterious. The accumulation occurs under the influence of ACC oxidase that prompts exudation of ACC, a precursor to ethylene synthesis. The PGPR capable of producing ACC deaminase degrades ACC into its intermediates i.e., ammonia and α-ketobutyrate, thereby, declining ethylene level and restoring plant development [30]. The inoculation of *Mucuna pruriens L.* (velvet bean), a well-adapted plant to arid and semi-arid regions with *Bacillus spp.* and *Enterobacter spp.* had shown significantly reduced ACC accumulation by 41% and 21% in leaves respectively, and in the roots by 46% and 15%, respectively. Thereby, the ethylene synthesis was reduced by 45% with *Bacillus spp.* (G9) and 65% with *Enterobacter spp.* (HS9) [29].

In addition to ACC deaminase activity, certain bacterial strains were found to be efficient in plant growth. For instance, *Achromobacter piechaudii* ARV8, a bacterial strain isolated from the arid region, experiencing frequent episodes of water stress was found to be better plant growth promoter as compared to *Pseudomonas putida* GR12–2, a bacterial strain inhabiting area with surplus water supply [31]. The bioinoculation of tomato (*Lycopersicum esculentum* Mill) and pepper (*Capsicum annuum L.*) seedlings with *A. piechaudii* strain improved relative water content (RWC) which subsequently succored plants in maintaining their fresh weight in water stress conditions. The maintenance of the fresh weight in bioinoculated seedling can be justified by the declined production of ethylene to 6.1 nlh^{-1} as compared to stressed seedling with the rise in ethylene level up to 23 nlh^{-1}. Overall, the plant biomass was enhanced four times as compared to uninoculated controls. Similarly bacterial strains mainly *Variovorax paradoxus, Pseudomonas spp. Achromobacter spp.* and *Ochrobactrum anthropi* islolated from rain-fed agricultural soil were reported to possess growth-promoting traits such as N_2 fixation, siderophore, and phosphate solubilization along with sufficient production of ACC deaminase. These bacterial strains both as single inoculation and consortium imparted significant growth, foliar concentration, and antioxidant activity to the wheat (*Triticum aestivum L.*) production [32].

The exopolysaccharide (EPS) released by PGPR tends to form rhizosheath or biofilms around the surface of the roots containing sufficient moisture content, thereby, protect them from prolonged desiccation. Moreover, plants inoculated with EPS are capable of accumulating sugars, amino acids, and proline. The survival of PGPR in dried sandy soils with low moisture content is conceivable due to EPS, which may serve as a biological tool to combat climatic water stress and ultimately providing a path towards global food security [33]. The coalition of ACC deaminase and EPS has been shown to have an affirmative effect on carotenoid pigments in certain plants. The inoculation of *Capsicum annuum* plants with *Bulkhorderia cepacia* (ACC deaminase activity 12.8 ± 0.44, mM αKB mg^{-1} min^{-1} and

EPS 4.89 ± 0.06 mg/mg protein) resulted in increased chlorophyll a and b content (chlorophyll a 5.7 gm L^{-1} and chlorophyll b 3.4 gm L^{-1}, respectively) as compared to control (chlorophyll a 3.2 gm L^{-1}, chlorophyll b 1.9 gm L^{-1}). Moreover, the plant biomass has also increased (fresh weight of 9 g and dry weight of 3.6 g) as compared to control (fresh weight 6 g, and dry weight 1.6 g) [34].

The co-application of PGPR producing ACC deminase with biochar has been utilized as an effective mechanism against prevalent water stress conditions. Timber-waste biochar was co-applied with *Bacillus amyloliquefaciens* strain to increase the productivity of wheat under simulated water stress conditions. Along with high productivity (59% of 100-grain weight), the grain composition (58% N, 18% P, and 23% K), carotenoid (114% chlorophyll a and 123% chlorophyll b), photosynthetic rate (118%), and transpiration rate (73%) in wheat were also reinforced [10]. To understand the PGPR potential for genetic improvement in plants, the physiology and biochemical characteristics of PGPR isolated from chickpea rhizosphere were implored. The seeds of chickpea were grown in the cultures of *Bacillus subtilis, Bacillus thuringiensis,* and *Bacillus megaterium*. The 25-day old chickpea seedlings were sprayed with plant growth regulators/plant growth retardants (PGRs) i.e., salicylic acid (SA) and putrescine (Put) at the rate of 150 mgL^{-1}. The consortium of PGPR and PGRs significantly improved carotenoid, sugar, and protein contents as compared to irrigated and non-irrigated conditions [14].

The inhibitory effect of water stress in two maize species was mitigated by inoculation with two endophytic bacterial species i.e., *Burkholderia phytofirmans* PsJN and *Enterobacter* sp. FD17 [35]. Maize seedlings were exposed to water stress after the 45th day of vegetative growth. The inoculated bacterial seedlings exhibited 30% relative water content in leaves along with the significant increase in root and shoot biomass, leaf area, chlorophyll content, and photochemical efficiency of PSII (Photosystem II). However, the *Paraburkholderia phytofirmans* PsJN was found to be more effective as compared to *Enterobacter* sp. FD17. The remedial potential of PGPR against water stress conditions can be used as a tool for sustainable agriculture practices (**Table 3**).

Treated Plant/PGPR	Stress Alleviation Effect
Maize/*Azospirillum lipoferum, Bacillus* Spp.	Increase accumulation of soluble sugar, free amino acids, proline and decrease electrolyte leakage, reduced activity of antioxidant enzyme [36, 37]
Soybean/*Pseudomonas putida* H-2-3	Lower the level of abscisic acid and salicylic acid and a higher level of jasmonic acid content; declined superoxide dismutase, flavonoids and radical scavenging activity [38]
Wheat/*Bacillus amyloliquefaciens, Azospirillum brasilense, Rhizobium leguminosarum, Mesorhizobium cicero, Rhizobium phaseoli*	Improved homeostasis; catalase, exo-polysaccharides and IAA production [39, 40]
Chickpea/*Pseudomonas putida*	Osmolyte accumulation, ROS scavenging ability and stress-responsive gene expressions [41]
Lettuce/*Azospirillum* sp.	Promote chlorophyll, ascorbic acid content and antioxidant capacity [42]
Rice/*Trichoderma harzianum*	Promote root growth independent of water status and delay drought response [43]

Table 3.
Alleviation of water stress via bioinoculants.

4. Amelioration of salinity via bioinoculants

The soil salinity is naturally occurring phenomena in arid and semi-arid regions. Besides, extensive use of chemical fertilizers and irregular irrigation practices, the continuously changing precipitation pattern is contributing 1–2% salinity to arable lands every year [44]. The plants growing under salinity conditions tend to have high levels of ethylene, stress hormone released in response to both biotic and abiotic stress. As mentioned earlier, PGPR possessing ACC deaminase enzyme can reduce ethylene level by disintegrating ACC (precursor to ethylene) into α-ketobutyrate and ammonia, thereby suppressing the formation of ethylene and ultimately sustaining the plant growth. In doing so, the strains of *Aneurinibacillus aneurinilyticus* and *Paenibacillus sp.* isolated from Garlic (*Allium sativum*) rhizosphere were used for seed bacterization of French bean (*Phaseolus vulgaris*) and evaluated for their ACC deaminase activity [11]. These strains produced more than ~1500 nmol of α-ketobutyrate mg protein^{-1} h^{-1} and more than ~30 μg/ml Indole Acetic Acid (IAA) under saline and nonsalinity stress conditions. Moreover, the seed bacterization in the form of consortia led to a ~ 60% decline in stress stimulated ethylene levels.

Under saline conditions, water uptake is restricted by ionic stress which develops between Na^+ and K^+ due to Na^+ accumulation in aerial parts of plants. Singh and Jha [12] successfully employed inoculation of *Stenostrophomonas maltophilia* SBP-9 on wheat (*Triticum aestivum)* and increased K^+ uptake by 20–28%. The plant-endophytic relationship has been explored by co-inoculation of *Cicer arietinum* (Chickpea) with *Bacillus subtilis* NUU4 and *Mesorhizobium ciceri* IC53 to alleviate salt stress. These bacterial strains increased proline accumulation which in turn sequestered hydrogen peroxide to strengthen the tolerance level against saline conditions. Besides, coinoculation of endophytes also reduced root rot infection caused by *F. Solani* [45]. The PGPR and their relationship with plants proved to be effective in dealing salt stress simultaneous to other biotic and abiotic stress in given global climatic conditions (**Table 4**).

5. Amelioration of oxidative stress via osmoregulation

Global climate change is amplifying the intensity of environmental factors, causing a profound disturbance in the plant's biological processes mainly via intractable generation of ROS. A condition called 'oxidative stress' develops when the available concentration of antioxidants within plant cells become insufficient to neutralize an unrestrained number of reactive species (OH^-, O^- and $H_2O_2^-$) which leads to disruption of cellular components (lipids, protein, nucleic acids, and metabolites). As a defense mechanism, plants and related rhizobacteria synthesize and release osmolytes when required. Osmolytes are low molecular organic compounds (proline: amino acids, sugars, polyols, methylamines, methylsulfonium compunds, and urea) mainly aiming at neutralization of the osmotic pressure of cells under stress conditions. These plants and PGPR synthesized osmolytes synergistically act to capture ROS. The prominent PGPR strains such as *Azospirillum brasilense* SP-7 and *Herbaspirillum seropedicae* Z-152 managed to retain relatively higher water content in vegetal tissues of inoculated/non-irrigated maize plants as compared to non-inoculated/irrigated maize plants. The plants inoculated with *H. seropedicae* had a higher proline accumulation rate (fourfold) as compared to those inoculated with *A. brasilense* (two-fold), thus indicating better osmoregulation under drought conditions. However, the amount of proline in inoculated plants

Treated Plant/PGPR	Stress Alleviation Effect
Groundnut/*Brachybacterium saurashtrense, Brevibacterium casei, Haererohalobacter*	Higher K^+/Na^+ ratio and higher Ca^{2+}, phosphorus, and nitrogen content, higher Shoot and root concentration of auxin [43, 46]
Mung bean/*Rhizobium, Pseudomonas*	ACC-deaminase activity [47]
Wheat/*Azospirillum* Sp., *Pseudomonas* Sp. *Serratia* Sp.	Osmotic adjustments via proline and soluble sugars [48]
	ACC deaminase activity, reduced ethylene level [49]
Maize/*Pseudomonas, Enterobacter*	More N, P, K uptake and high K^+–Na^+ ratios [50]
Rice/*Pseudomonas pseudoalcaligenes, Bacillus pumilus, Bacillus amyloliquefaciens*	Reduced reactive oxygen species, lipid peroxidation and superoxide dismutase activity, modulating differential transcription in at least 14 genes [51, 52]
Lettuce/*Azospirillum*	Promoted ascorbic acid content antioxidant capacity [42]

Table 4.
Alleviation of salinity stress via bioinoculants.

was relatively lower than control plants in both water-stressed and well-watered conditions. This decreased concentration of proline in inoculated plants may be attributed to a balanced amount of osmolytes to the available ROS leading to better osmoregulation in water-stressed conditions. Also, inoculated plants have lower ethylene content than that of control plants. However, the gene expression of ZmVP14 responsible for the biosynthesis of abscisic acid was suppressed in inoculated plants [53], allowing stomata to remain open for better CO_2 assimilation even in drought conditions also supported by other researchers [35].

Inoculation of chickpea varieties with *Pseudomonas putida*, also indicated reduced proline concentration with a reduced level of 114% in BG-362 and 214% in BG-1003 on the seventh day of water stress [41, 53]. However, in *Capsicum annum* inoculated with *Burkholderia cepacia*, the accumulation of proline content was higher (0.143 mmoles gm^{-1}) as compared to *the* control plant (0.065 mmoles gm^{-1}). Co-inoculation of *Azotobacter chroococcum* and *Azospirillum brasilense* significantly improved accumulation of proline and other osmolytes along with physic-chemical characteristics of *Mentha pulegium L.* [54]. Other than proline, some soluble sugars play a vital role in maintaining photosynthesis in leaves under water stress, therefore, also termed 'osmoprotectant'. However, the reduced level of soluble sugar can become deleterious to the cellular membranes of plants. The co-inoculation of PGPR (*Bacillus subtilis*, *Bacillus thuringiensis*, and *Bacillus megaterium*) with PGRs (SA & Put) in chickpea seedlings prompt the accumulation of soluble sugar along with chlorophyll and protein content (majorly proline), thus, regularizing photosynthesis under water stress [14]. The accumulated soluble sugar also acts as a signaling molecule, where it triggers the activation and gene expression of certain genes relevant to photosynthesis in plants. Hence, osmolytes being 'abiotic stress busters' are pivotal in maintaining homeostatic equilibrium at the molecular and cellular level to enhance stress tolerance in plants [55].

6. Amelioration of cold stress via psychrotrophic microbes

Due to global warming, extreme environmental conditions are occurring more frequently including cold stress. In northern parts of the world, the cold weather is unexpectedly intensifying specifically due to the Polar vortex bringing cold Arctic air towards southern parts of the planet, bringing more intense winters in some parts of the world. The biomes of extreme environments serve as excellent habitats for archaea, bacteria, and fungi. Agro-ecosystems at high altitudes are vulnerable to low productivity due to low surface temperature resulting in low soil temperature and in turn low soil fertility [56]. High altitude soils comprised diverse microbes that are capable of surviving cold environments mainly due to synthesis and assimilation of cryoprotective compounds such as metabolites (proline), anthocyanin (secondary metabolite), and carbohydrates (trehalose). The induction of such stress-resistance against abiotic stress is also coined with a term called 'Induced Systematic Resistance' (ISR). An in vitro inoculation of *Vitis vinifera L.* (grapevine) explants with *Burkholderia phytofirmans* strain PsJN successfully developed chilling resistance mainly via accumulation of increased level of sugars, proline, and phenolics as compared to non-inoculated plantlets [57].

Several biotechnological and microbiological attempts have been ongoing for the last two decades to utilize the cold-tolerant (psychrotrophic) or cold-loving (psychrophilic) microbes to improve the agricultural practices in chilling mountainous environments. Psychrophilic microbes inhabiting cold environments majorly belong to phyla *Verrucomicrobia*, *Thaumarchaeota*, *Spirochaetes*, *Proteobacteria*, *Planctomycetes*, *Nitrospirae*, *Mucoromycota*, *Gemmatimonadetes*, *Firmicutes*, *Euryarchaeota*, *Cyanobacteria*, *Chloroflexi*, *Chlamydiae*, *Basidiomycota*, *Bacteroidetes*, *Ascomycota*, and *Actinobacteria*. Like thermotolerant PGPR, the psychrotrophic PGPR explicit various attributes like ACC deaminase activity, solubilization of micronutrients (phosphorus, potassium, and zinc), biological N_2 fixation, and production of ammonia, hydrogen cyanide, indole-3-acetic acid, and Fe-chelating compounds (**Figure 2**). The alleviation of cold stress on the production of cereal crops such as wheat was investigated by inoculation with *Bacillus spp.* CJCL2 and RJGP41 strains isolated from Qinghai-Tibetan plateau [58]. The psychrophilic activity of this strain was also compared to temperate *B. velezensis* FZB42 at a temperature range of 14°C, 10°C, and 4°C after 4 h post-inoculation. The cold-tolerant strain CJCL2 produced the finest biofilm structure as compared to RJGP41 which produced slight biofilms at 96 h post-inoculation at 4°C, whereas FZB42 failed to develop any biofilm at 4°C. The basic mechanism against cold stress was based on the regulation of abscisic acid, lipid peroxidation and proline accumulation, and a lower level of ROS. Moreover, genetic expression for ACC deaminse, glucose dehydrogenase encoding phosphate solubilization, and phytohormones was quite effective and led to the improvement in plant growth under cold stress. The cold-tolerant *Bacillus* spp. maintained osmotic balance in a plant cell by synthesizing glycine betaine, a major osmoprotectant and produced due to OpuAC gene expression. All in all linear four-fivefold increase in the gene expression of cold shock proteins (CspB, CspC, and CspD) observed in CJCL2 and RJGP41 inoculated wheat

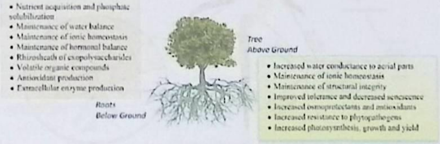

Figure 2.
Key mechanisms targeted by plant growth promoting rhizobacteria.

plants may trigger the modifications in RNA. Also, these proteins may stabilize the secondary structure of nucleotides leading to improved cellular components.

6.1 Plant growth promoting rhizobacteria and root-nodule symbiosis

The PGPR possessing root-nodule symbiosis has also been reported to exhibit psycrotolerant traits at 5°C [59]. These PGPRs were isolated from the root nodule of *Pisum sativum L.* (Pea), cultivated in the Northern Indian plains. Out of nineteen tested strains, four exhibited cold tolerance mainly by producing phytohormone IAA in the range of 62.7–198.1 μg/ml. The inoculation of edible crops growing under adverse climatic conditions with PGPR producing phytohormones showed promising results [60]. The *Serratia nematodiphila* PEJ1011 strain was inoculated to *Capsicum annuum L.* (pepper) at a low temperature of 5°C. The inoculated plants exhibited higher endogenous GA_4 content grown both at normal and low temperatures. Moreover, PGPR increased abscisic acid (phytohormone) level and reduced jasmonic acid and salicylic acid (phytohormones) contents to regulate plant adaptation and growth at low temperature (**Figure 3**).

6.2 Plant growth promoting rhizobacteria and chlorophyll pigments

Chloroplasts containing chlorophyll pigments for photosynthesis are the main organelles affected by the cold. Low temperature also led to stomatal closure in many cold-tolerant plants like *Arabidopsin thliana*. Although the stomatal closure prevents leaf dehydration, CO_2 uptake is inhibited which eventually reduces photosynthesis. The inoculation of *A. thliana* with endophytic *Burkholderia phytofirmans* strain PsJN (Bp PsJN) prevented disruption of the plasma membrane at 0°C, −1°C, and − 3°C and induced cell wall strengthening in leaf cells [62]. Moreover, after night stress, the bacteria led to better photosynthetic pigment content. Similarly, *Vitis vinifera L.* (grapevine) cultivated in temperate and cool climates contains CBF4 gene which is a homolog to *A. thliana* CBF1 accumulates carbohydrates and proline on exposure to low temperature [63]. The *V. vinifera* plantlets were inoculated with endophytic *B. phytofirmans* strain PsJN at 4°C. As expected, the bacterial strain had induced cold resistance principally by enhancing gene expression of CBF (specifically CBF4) genes, along with an accumulation of anti-freeze proteins (PR proteins) and metabolite level. The bacterial strain was found to be highly effective in inhibiting hydrogen peroxide (H_2O_2). However, the inoculated plantlets indicated high H_2O_2 accumulation

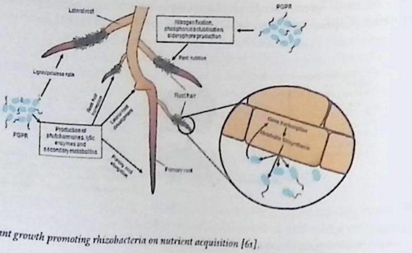

Figure 3.
Impact of plant growth promoting rhizobacteria on nutrient acquisition [61].

in the first three days of cold stress followed by H_2O_2 elimination after a week, further evidenced by a reduction in the level of metabolites after 1 week indicating inhibition of ROS via scavenging process carried out by endophytic PsJN strain.

6.3 Plant growth promoting rhizobacteria and sugar deposition

Certain bacteria, fungi, vascular plants, and invertebrate animals synthesize trehalose or mycose for energy consumption and to tolerate cold and water stress. Trehalose is a disaccharide sugar consisting of two glucose molecules mainly synthesized via phosphorylated intermediate trehalose 6-phosphate (T6P). Being capable of inducing cryoprotective compounds, *B. phytofirmans* strain PsJN was inoculated in grapevine to observe its impact on the accumulation of T6P and trehalose at 4°C. After 120 h of cold exposure, the level of T6P was increased in roots (>0.4 nmol. g^{-1} FW) stems (>0.7 nmol. g^{-1} FW), and leaves (>1.7 nmol. g^{-1} FW) of inoculated plantlets. T6P acts as a signal metabolite in plants responding in particular to changes in sucrose level, thereby a strong correlation had been observed between T6P and sucrose content in all plant organs in both chilled and non-chilled plants. The authors were uncertain about the role of trehalose against chilling because the overall accumulation of trehalose was only found in leaves in low amounts i.e., <15 nmol. g^{-1}. Localized trehalose accumulation might have protected cell membranes against cold-induced dehydration [64, 65]. However, the organ-specific accumulation may indicate trehalose acted as an osmolyte [66]. Previous studies related to drought stress indicated overexpression of genes for the synthesis of trehalose which under water-stress inhibited dehydration [67]. Although psychrotolerant PGPRs are proved to be effective in inducing tolerance against cold stress, the quest of mechanism underlying is still being investigated by the researchers.

7. Conclusions

Despite awareness and efforts being planned or carried out, global temperature, a dynamic entity itself is hard to reverse to its previous levels in 1990. Instead, plant species have to acclimatize themselves to prevailing temperature variations. A natural symbiotic relationship between PGPR and plant growth is known for decades, has been widely considered and accepted as the most convenient and reliable approach to deal with climate-based environmental stresses. This chapter, therefore, quoted and discussed several research studies utilizing PGPR to alter physiological and biochemical processes occurring at inter and intracellular levels to boost the plant's defense mechanism. However, the complexity of the mechanism underlying is still in focus to fully harness the potential of PGPR for sustainable agricultural practices and for sustaining natural plant diversity.

Conflict of interest

The authors declare no conflict of interest.

Abbreviations

PGPR	Plant Growth Promoting Rhizobacteria
1-Aminocyclopropane-1-carboxylate Deaminase	ACC deaminase

ABA	Abscisic Acid
SA	Salicylic Acid
IAA	Indole-3-Acetic Acid
VOCs	Volatile Organic Compounds
ABA	Abscisic Acid (ABA)
HSP	Heat Shock Protein
SOD	Superoxide Dismutase
POD	Peroxidase
CAT	Catalase
ROS	Reactive Oxygen Species
RWC	Relative Water Content
EPS	Exopolysaccharide
PGRs	Plant Growth Retardants (PGRs)
Put	Putrescine
ISR	Induced Systematic Resistance

Author details

Rafia Younas[1], Shiza Gul[1], Rehan Ahmad[1], Ali Raza Khan[1], Mumtaz Khan[2], Tauseef Anwar[3] and Huma Qureshi[4*]

1 Department of Environmental Science, Institute of Soil and Environmental Sciences, Gomal University, Dera Ismail Khan, Pakistan

2 Directorate of Regional Services, Allama Iqbal Open University, Islamabad, Pakistan

3 Department of Botany, The Islamia University of Bahawalpur, Bahawalnagar Campus (New Campus), Bahawalnagar, Pakistan

4 Institute of Biological Sciences, Gomal University, Dera Ismail Khan, Pakistan

*Address all correspondence to: drhuma@gu.edu.pk

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Chapter 15

Strategies and Programs for Improved Nutrient Use Efficiency, Doubling Farmer's Income, and Sustainable Agriculture: Indian Context

Ravinder Juttu, Kamalakar Jogula, Subhashree Priyadarshini, Sharan Bhoopal Reddy, Prasanta Kumar Patra, Bairi Raju, J.D. Saritha, Princy Thakur, S. Rakesh, Jogarao Poiba, A. Krishna Chaitanya and Kiran Pilli

Abstract

Since the Green Revolution era, the farming sector exploited the soils for food, fiber, fodder, etc., with high input responsive varieties that excavated vast amounts of chemical fertilizers. The burgeoning population of the country calls for a commensurate increase in food production to satisfy the demands of its inhabitants. Further, due to innovative mechanization in agriculture, specialization, and government policy programs, the productivity of food has soared. Subsequently, it ensued greater productions and minimized food prizes. Regrettably, intensive agricultural operations degraded the soil quality and now reached such a stage where without external inputs, growers unable to achieve their targeted yields. India has lost 68% innate productive capacity of agricultural soils. This plunder of land's quality continues unabated, further resulting in low nutrient use efficiency and insufficient yields of agroecosystems. Therefore, this is high time to realize the dreadful impacts of intensive crop production on the natural ecosystem. Irrefutably, both soil and its nutrients are the wondrous gifts of nature to humankind; utilizing them sustainably is imperative. The present chapter highlights the impacts of non-judicious nutrient management on soil productivity, nutrient use efficiency, and novel technologies required to promote sustainable agriculture and achieve the target of doubling farmer's income in India.

Keywords: Food security, sustainability, nutrient use efficiency, technologies

1. Introduction

The agriculture sector is the primary source of livelihood for over 58% of the Indian population and a key contributor to the health of the country's economy as it contributes approximately 17.1% to India's gross value added (GVA). It generates an

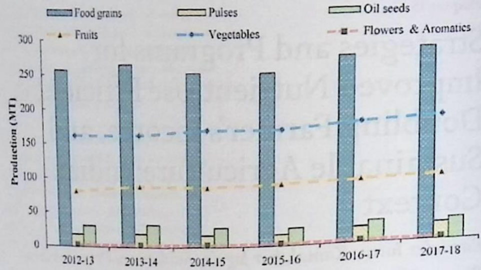

Figure 1.
Production rates of different agricultural produce in India [1].

employment opportunity for 44% of its workforce. Agriculture in India, continues to make impressive progress, while food grain production at record 296.7 million tons (Mt) and total oilseeds production at record 33.4 Mt., during 2019–2020. Such increments were also observed in other major crops. Current production estimates show that food grains, pulses, oilseeds, fruits, vegetables, and flower and aromatics are about 284.83, 25.23, 31.31, 97.35, 184.39, and 3.65 Mt., respectively. The production rates of different agricultural produce in India for the period from 2012 to 2013 to 2017–2018 are presented in **Figure 1.** Despite this remarkable growth in production in India, about 14.8% of the population and 38.4% of children remain malnourished. As per evaluation of the Global Food Security Index (GFSI), India ranked 76th out of 113 countries.

Only agriculture can help us achieving food security in the country. Since the green revolution (GR) in India, growers are cultivating high-yielding varieties under the irrigated condition with high amount of fertilizer nutrients and pesticides, saved millions of lives from starvation, and transformed India into a self-sufficient country in food production; also from the status of a "hungry nation" to that of a "food exporting nation" [2]. But, because of burgeoning population pressure and restricted land usage, it has become a serious challenge. Intensive agricultural operations involving continuous tillage and chemical fertilizers and pesticides are a concern in terms of environmental issues and soil degradation in the post-green revolution period. Increasing food demand has laid more stress on the agricultural soils for increased productivity. The total NPK fertilizer consumption during 2018–2019 was 27.23 Mt. and it is likely to increase to around 48.0 Mt. by 2050.

The persistent decline in nutrient use efficiency, soil fertility status, and environmental quality are the key constraints coming in the way of achieving sustainability in Indian agriculture. Specifically, in the Indian soils, nutrient use efficiency (NUE) is very low. It varies from 30 to 50% for nitrogen (N), 15 to 20% for phosphorus (P), 60 to 70% for potassium (K), 8 to 10% for sulphur (S), and 1 to 2% for micronutrients [3]. The unutilized N is lost through several mechanisms such as leaching, denitrification, volatilization, etc., pollute the groundwater and atmosphere. Considerable amounts of P and K are also lost through soil erosion. As per the estimation, annually, over 5.3 billion tonnes (Bt) of soil is lost through water erosion that ultimately results in the loss of about 8 million tonnes (Mt) of plant nutrients (NPK). Finally, there exists a huge yield gap (difference between the achievable and the actual yield) in most of the crops of India.

Yet the production of food, fiber, and raw materials must be enhanced in a sustainable manner to the demands of the ever-growing and progressively affluent population of India. Whereas the inorganic inputs supplying for the food production may never be completely replaced by the organic amendments but with appropriate management strategies/technologies, we could be able to achieve higher nutrient use efficiency, minimize the adverse impacts on the environment, and double the farmer's income that brings sustainability in the agricultural production system.

2. Technological options suitable for Indian agriculture

2.1 Enhancement of soil organic carbon

Improving SOC in agricultural soils is now a global challenge for environmental safety [4, 5] as it is the most realistic approach to regulate soil degradation [6] and improve soil productivity to achieve higher crop yields [7–10]. It has several benefits on soil quality maintenance as showed in **Figure 2**. Mahmood et al. [11] revealed in his experiment that incorporation of OC into the soil system through sheep manure (SM), farmyard manure (FYM), and poultry manure (PM) alone or amalgamation with chemical fertilizers significantly improved the soil organic carbon status as well as the available total nitrogen (TN), total phosphorus (TP) and total potassium (TK) (**Figure 3**) over the control and complete inorganic treatment. Improvement in soil fertility always has a direct benefit on crop yields as the availability of all essential soil nutrients increases through the addition of C input. There was an increase in crop yields (kg ha^{-1}) for every Mg ha^{-1} increase in SOC stock in the root zone. A field experiment conducted to evaluate the effect of C input under various crop production systems showed that an improvement in crop yields (kg ha^{-1}) such as 170 for pearl millet, 145 for soybean, 150 for castor, 160 for upland rice, 18 for

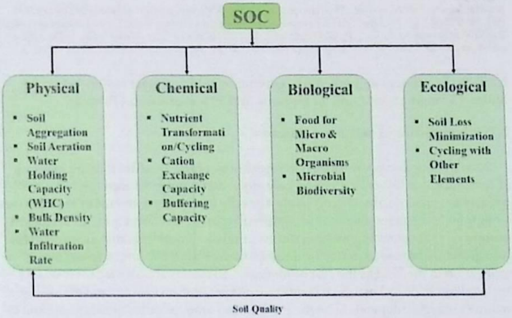

Figure 2.
Important SOC functions in soil quality maintenance.

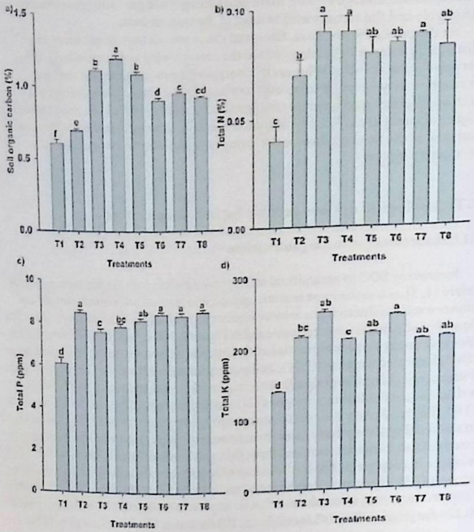

Figure 3.
Residual Impact of sheep manure (SM), farmyard manure (FYM), and poultry manure (PM) on (a) SOC (%), (b) TN (%), (c) TP (ppm), (d) TK (ppm) after crop harvest (Source: [11]). T1: Unfertilized control; T2: NPK at 250–150-125 kg ha^{-1}, T3: SM at 15 t ha^{-1}; T4: FYM at 16 t ha^{-1}; T5: PM at 13 t ha^{-1}; T6: NPK at 150–85-50 + 8 t ha^{-1} SM, T7 NPK at 150–85-50 + 8.5 t ha^{-1} FYM; T8: NPK at 150–85-50 + 7 t ha^{-1} PM 2.2.

lentil, 90 for winter sorghum, 33 for groundnut, 124 for finger millet, 101 finger millet, 13 for groundnut, 145 for soybean, and 59 for safflower (**Table 1**).

2.2 Organic manures and green manures

Manures are the decomposed heterogeneous organic mixture that are made up of farm wastages like crop residues, cow dung, and household wastages. Manure releases the plant nutrients very slowly, thus the initial requirements of the crop met by supplying fertilizer nutrients for optimum growth and development. Farmyard manure (FYM) contains almost all the essential plant nutrients that are needed for crop growth. Farmers in India could easily manage the FYM preparation and its application in the field as the cost of inorganic fertilizers are high which is unable to afford by small and marginal farmers. However, the availability and efficiency of manure are highly dependent on the method and amount of its application, time to incorporate, and decomposition rate by soil microorganisms.

Green manures (GM) where leguminous crops are incorporated into the soil during the flowering stage that makes the soil fertile and increases crop productivity.

Cropping system	Mean annual C input ($Mg\ C\ ha^{-1} year^{-1}$)	Yield increased ($kg\ ha^{-1}$)	Reference
Pearl millet- Cluster Bean- Castor	0.2–1.9	Pearl millet- 170 Cluster Bean- 140 Castor- 150	[12]
Groundnut	0.5–3.5	Groundnut- 13	[13]
Finger millet	0.3–3.1	Finger millet- 101	[14]
Groundnut-Finger millet	0.3–3.0	Groundnut- 33 Finger millet- 124	[15]
Soybean-Safflower	1.9–7.0	Soybean- 145 Safflower- 59	[16]
Winter Sorghum	0.6–3.4	Winter Sorghum- 90	[17]
Rice-Lentil	1.1–5.6	Upland rice- 160 Lentil- 18	[18]

Table 1.
Effect of mean annual C input on Crop yields under various cropping systems.

These manures are a great source of biologically fixed N and organic carbon. The area for green manuring crops is limited to 7 Mha in India [19] and has also not expanded over the last few decades. Probably, the low price of urea N, intensification in crop production, scarcity of land, and irrigation water are the main factors for the long-term reduction in GM use. Legume crops like mungbean/cowpea or typical GM crops like *dhaincha*/sunn hemp can be grown and incorporated into the soil. GMs have the capacity to meet the N demands of the crops. A 40–45 days old GM crop can supply 100–125 kg N which is equal to the N requirement for cereal crops [20] Even after harvesting the pods, residues can be incorporated into the soil, which saves around 60 kg N ha^{-1} in succeeding crops like rice or maize [20, 21].

2.3 Integrated nutrient management

Integrated nutrient management (INM) is a technique of combined usage of chemical fertilizers, organic amendments, and bio-fertilizers in farming which is an economically feasible and environmentally benign way of managing plant-available nutrients. This concept originated at the beginning of the 1990s because of the widespread emergence of multi-nutrient deficiencies and soil degradation. Thus, INM comprises major objectives such as soil fertility maintenance, sustenance of crop productivity, and improvement of the farmers' profitability. The amalgamation of inorganic fertilizers with organic amendments aids in the provision of improving soil productivity by improving soil C storage [10, 22]. The INM-induced SOM build-up aids in the provision of improved soil structure and water holding capacity that directly enhances crop yields.

A long-term field experiment showed higher grain yield and sustainability yield index (SYI) of maize and black gram under the INM treatment (conjunctive use of fertilizers and organic amendments) as compared to sole inorganic treatment and control (**Figure 4**) [10]. Such improvements in yields may be due to the continuous addition of C inputs that creates a congenial environment for plant growth by modifying the soil's physical properties [23, 24]. The importance of INM practice for increasing soil health, nutrient use efficiency, crop yields, and decreasing environmental pollution has been recorded by several researchers in the Indian subcontinent [25, 26]. The location-specific INM strategies working better under various cropping systems are summarized in **Table 2**.

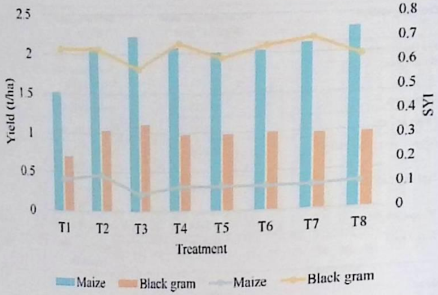

Figure 4.
Mean crop yields and sustainability yield index of maize-black gram system as influenced by the INM approach (Source: [10]). T1: Control; T2: 100% RDF of NP; T3: 25 kg ha^{-1} N (FYM) + 25 kg N (Urea) + 30 kg P ha^{-1}; T4: 25 kg ha^{-1} N (Compost) + 25 kg N (Urea) + 30 kg P ha^{-1}; T5: 25 kg ha^{-1} N (Crop residue) + 25 kg N (Urea) + 30 kg P ha^{-1}; T6: 15 kg ha^{-1} N (FYM) + 10 kg N (Crop Residue) + 25 kg N (Urea) + 30 kg P ha^{-1}; T7: 15 kg ha^{-1} N (FYM) + 10 kg N (Compost) + 25 kg N (Urea) + 30 kg P ha^{-1}; T8: 15 kg ha^{-1} N (FYM) + 10 kg N (Green Leaf) + 25 kg N (Urea) + 30 kg P ha^{-1}.

2.4 Conservation agriculture

Traditional agriculture, based tillage, and other management operations lead to soil erosion problems, surface and groundwater pollution [27]. Conservation agriculture (CA) technology involving three basic principles such as minimum soil disturbance, efficient and diversified crop rotations, and surface crop residue retention aids in the provision of enhancing/improving soil organic carbon storage. Tillage and residue management greatly influence the soil's physicochemical and biological properties [28]. Zero tillage (ZT) for crop production has been identified as an important practice to increase soil aggregation and C sequestration [28] as compared with traditional systems i.e., conventional tillage (CT).

Adoption of ZT in wheat production in India, reduced the cost of production by Rs 2,000 to 3,000 ha^{-1} ($ 33 to 50) [29]; enhanced the soil quality, [30]; improved C sequestration and mitigation of Green House Gas emissions [31]; reduction in weed population *Phalaris minor* in wheat (Malik et al., 2005), enhanced water and nutrient use efficiency [31, 32] and overall increments in production and productivity (4–10%) [33]. The practice of ZT significantly increased the soil total nitrogen content (**Figure 5**) in both rice-wheat and rice-maize cropping systems in both districts studied in West Bengal [34]. CA adoption in India is still in the initial phases. Over the past few years, the adoption of ZT expanded to cover about 1.5 Mha [32].

2.5 Pulses in crop rotation

Meeting the N demands of the crop efficiently with fewer N losses and more use efficiency is a critical challenge for the food production community [35]. Many researchers reported that pulse crops can significantly improve soil nitrogen availability, soil water conservation, and increase total system productivity. Gan et al. [36] reported that the practice of growing pulses helps in biological fixation of atmospheric N_2, increases total grain production by 35.5%, protein yield by 50.9%,

Location/system	Kharif	Rabi
Rice-wheat		
Jammu, Jammu and Kashmir Palampur, Himachal Pradesh	50% NPK through fertilizers +50% NPK through FYM 50% NPK through fertilizers +50% N through organic sources such as FYM green manure and wheat straw	100% NPK through fertilizers
Kalyani, West Bengal	50% NPK through fertilizers +50% N through FYM/green manure or rice straw	100% NPK through fertilizers
Navsari, Gujarat	75% NPK through fertilizers +25% N through FYM or green manure	
Faizabad, Uttar Pradesh	50% NPK through fertilizers +50% N through FYM or green manure	100% NPK through fertilizers
Rice-rice		
Jorhat, Assam Karamana, Kerala	75% NPK through fertilizers +25% N through rice straw 50–75% NPK through fertilizers +25–50% through FYM or crop residue or green manure	75% NPK through fertilizers
Siruguppa, Karnataka	50–75% NPK through fertilizers +25–50% N through rice straw or *glyricidia* green leaf manure	100% NPK through fertilizers
Rajendranagar, Telangana	50% NPK through fertilizers +50% N through *glyricidia* green leaf manure	100% NPK through fertilizers
Rice – Maize		
Kathalgere, Karnataka	75% NPK through fertilizers +25% N through FYM or paddy straw or*glyricidia* green leaf manure	100% NPK through fertilizers
Pearl Millet – Wheat		
S.K. Nagar, Gujarat	50–75% NPK through fertilizers +25–50% N through FYM/wheat straw/sunhemp	75% NPK through fertilizers
Bichpuri, Uttar Pradesh	50–75% NPK through fertilizers +25–50% through FYM or green manuring	75% NPK through fertilizers
Sorghum – Wheat		
Akola, Maharashtra	50% NPK through fertilizers +50% N through FYM or wheat straw or *Leucaena* loppings	100% NPK through fertilizers
Rahuri, Maharashtra	50% NPK through fertilizers +50% N through FYM	100% NPK through fertilizers

Table 2.
Best INM treatments practicing under various cropping systems of India.

and fertilizer-N use efficiency (FUE) by 33.0% over the summer fallow system. Diversifying cropping systems with pulses such as dry pea (*Pisum sativum* L.), lentil (*Lens culinaris* Medikus), and chickpea (*Cicer arietinum*), etc. can serve as an effective alternative to summer-fallowing in rainfed dry areas. These pulses could increase the systems' productivity and decreases the negative impacts on the environment.

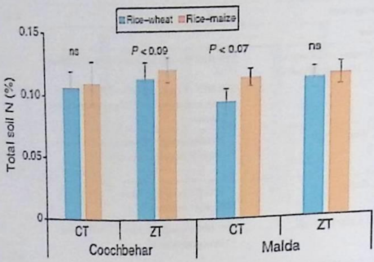

Figure 5.
Effect of ZT and CT on total soil N (0–10 cm) under rice–wheat and rice–maize systems at different districts of West Bengal (Source: [34]).

The inclusion of pulse crops in the crop rotation aids in the provision of improved crop yields and decreased N fertilizer requirements [37] and enhanced nitrogen use efficiency [38]. Pulse crops provide a large portion of N requirements to subsequent cereal crops and maintain economic returns [39]. Reduction in N fertilizers requirements naturally reduced the cost of cultivation thereby benefiting the farmers with less expenditure. Long-term experiments revealed that crop diversification with pulses and oilseed can help farmers to improve overall agricultural sustainability [40].

2.6 Fertigation and foliar spraying

Fertigation is a technique of supplying plant nutrients along with irrigation which helps in increasing crop yields or N fertilizer efficiency in many conditions with different crops [41]. Supplement of N and P fertilizer through fertigation technique significantly enhanced the wheat grain yield by 16% as compared to top-dressed N [42]. The fertigation process allows the soil to absorb up to 90% of supplied nutrients, while it is only about 10 to 40% under dry fertilizer or granular application. It ensures saving in fertilizer quantity of about 40–60%, because of better fertilizer use efficiency and reduced leaching losses [43]. Application of liquid biofertilizers and mineral fertilizers along with drip fertigation in green gram cultivation significantly increased the number of pods plant, number of seeds pod^{-1}, test weight, seed yield, and haulm yield [44]. Manikandan and Sivasubramaniam [45] reported that drip fertigation with 100% recommended dose of fertilizer through water-soluble fertilizers + foliar feeding with 0.5% $ZnSO_4$ resulted in the highest onion bulb yield and quality. Various advantages of fertigation in agriculture production are illustrated in Figure 6.

The positive effects of foliar spraying of zinc nano-fertilizer on vegetative growth parameters of pearl millet [46] on and snap bean plants [47] are reported. Foliar application of micronutrients increases the vegetative growth, consequently higher production capacity which reflected in the quality of barley [48] and faba bean [49].

2.7 Water-soluble fertilizers

Water-soluble fertilizers are 100% soluble in water which is suitable for foliar application due to their low salt index to reduce the potential for the burning of

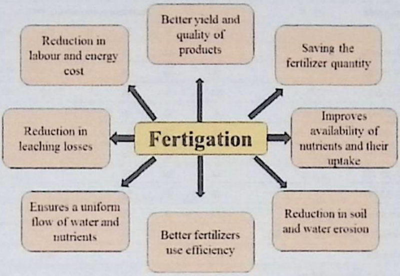

Figure 6.
Advantages of fertigation technique in agriculture.

plant tissue. It is also used in fertigation, sprinkler, or drip irrigation systems to increase yield and to improve the quality of fruits and vegetable crops. These fertilizers should meet certain criteria such as 100% solubility, high purity, low salt index, (EC = 0.9–1.2), pH acidic (5.5 to 6.5), and no inert matter, free from sodium and chloride, driven by R&D, suitable for fertigation and foliar application, higher nutrient use efficiency, etc. These fertilizers are mostly the combination of N, P, K, Ca, Mg, S, and micronutrients with different ratios developed to suit the type of crop, quality of water, soil fertility, and climatic conditions [50]. The Fertilizer Control Order (FCO) approved water-soluble fertilizers and their nutrient composition is presented in **Table 3**.

2.8 Biofertilizers

Biofertilizers are the source of microbial inoculants prepared in a controlled laboratory condition that acts as a substituent for chemical fertilizer and helps to achieve sustainable agriculture [51] boosting farm productivity [52]. Several studies indicated the use of biofertilizers in agriculture enhanced crop yields at greater levels. Usage of biofertilizers such as *Azotobacter*, *Azospirillum*, *Rhizobium* for N, and phosphate solubilizing bacteria (PSB) for P, vesicular-arbuscular micorhizae (VAM) for other nutrients availability in crop cultivation helps in improving crop yields and quality. Soil inoculation with *Azotobacter*, *Azospirillum*, and PSB produced maximum crop yields by 5–10% over farmers' practice [53]. In another study under jute, the yield was increased by 19% due to biofertilization over RDF, rice by 8% and green gram by 12%. Rao [53] studied the effect of BF on nutrient recovery. The study revealed that NPK recovery increased from 62.0% to 74.0% in recommended fertilizers + BF treatment. Combining soil test based fertilizer recommendation with organics and biofertilizers under maize cultivation considerably enhanced the recovery of N from 18–66%, P from 9–36%, K from 33–88%, and S from 17–34% [54] (**Table 4**). ICAR is also promoting the development of biofertilizers consisting of *Azospirillum lipoferum*, *Azotobacter chroococcum* and plant growth promoting *Rhizobacteria* (PGPR Mix I). But in India, the current supply position is very low (<100, 000 t), as the total anticipated biofertilizers demand is 1 Mt. [53].

Product (grade)	Nutrient composition (%)						
	N	P	K	S	Ca	Mg	Zn
NPK (13-40-13)	13	40	13				
NPK (18-18-18)	18	18	18				
NPK (13-5-26)	13	5	26				
NPK (6-12-36)	6	12	36				
NPK (20-20-20)	20	20	20				
NPK (19-19-19)	19	19	19				
NPK (12-30-15)	12	30	15				
NPK (12-32-14)	12	32	14				
Potassium nitrate (13-0-45)	13	0	45				
Mono potassium phosphate (0-52-34)	0	52	34				
Calcium nitrate	15.5				18.8		
Potassium magnesium sulphate			22	20		18	
Mono ammonium phosphate (12-61-0)	12	61	0				
Urea phosphate (17-44-0)	17	44	0				
Urea phosphate with SOP (18-18-18)	18	18	18	6.1			
NPK Zn (7.6-23.5-7.6-3.5)	17.6	23.5	7.6				3.5

Table 3.
FCO approved 100% water-soluble fertilizers (Source: [50]).

Treatment	Nutrient (%)			
	N	P	K	S
Soil test based fertilizer	18	9	33	17
Soil test based fertilizer + Organics	59	30	80	26
Soil test based fertilizer + Organics + Bio fertilizers	66	36	88	34

Table 4.
Apparent recovery of nutrients as affected by different treatments under maize cultivation (Source: [54]).

2.9 Nano fertilizers

Regular synthetic fertilizers are highly vulnerable to the losses such as leaching, volatilization, percolation, etc. which ultimately results in low NUE which is below 30%. "Nano fertilizers" are prepared by extracting the nutrients from different parts of the plant through chemical, physical, mechanical, or biological methods using nanotechnology. Nanotechnology has a long-term impact on agriculture and food production as the usage of these fertilizers in farming improves crop growth, yield, and quality parameters while increasing the nutrient use efficiency (NUE), and reducing the wastage and cost of cultivation. A significant higher selenium uptake was observed in the plots where nano-sized particles were applied [55]. Nano-fertilizers in agriculture enhanced nutrient uptake and crop productivity [56, 57]. The percent yield increased in different crops due to the addition of Nano-fertilizers illustrated in the table below (**Table 5**).

2.10 Customized fertilizers

Customized fertilizers (CF) are multi-nutrient (macro-N, P, K, secondary-Ca, Mg, S, and micro nutrient-Zn, Cu, B, Fe, Mn, etc.) produced from both inorganic

Nano fertilizer	Crops	% Yield increased
Aqueous solution on nano iron	Cereals	8–17
Nano silver + allicin	Cereals	4–8.5
Nano fertilizer + urea	Rice	10.2
Nano-encapsulated phosphorous	Vegetables	12.0–19.7
Rare earth oxides nanoparticles	Vegetables	7–45
Nano chitosan-NPK fertilizers	Wheat	14.6
Nano chitosan	Tomato	20.0
Nano powder of cotton seed and ammonium fertilizer	Sweet potato	16
Nanoparticles of ZnO	Cucumber	6.3

Table 5.
% yield increased by the application of nano fertilizer in different crop production (Source: [56]).

and organic sources, manufactured through a systematic process of granulation designed to facilitate the availability of a complete range of nutrients to the plant growth during its growth stages [58]. It has various advantages besides soil health enhancement and maximum crop yields (**Figure 7**). On the basis of nutrient uptake, total soil fertility status, crop nutrient requirement, and fertilizer nutrient to be applied and its use efficiency, grades of the CF are prepared [59]. Different forms of CF available across various geographical areas of India presented in **Table 6.**

2.11 Sensors based technologies for irrigation and fertilization

A new approach of collecting real soil moisture using sensors offers real potential for reliably monitoring the status of soil water in croplands [60]. The use of sensor technology for an automatic irrigation system is highly economical

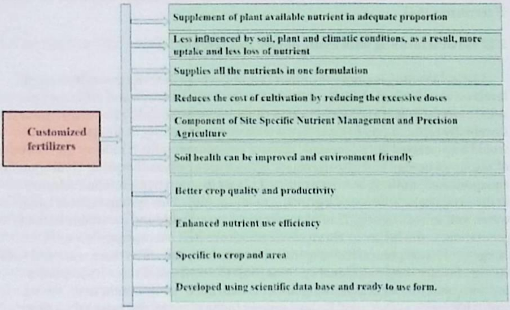

Figure 7.
Advantages of using customized fertilizers in agriculture.

Crops	Formulations (N:P:K:S:Zn:B)/ N:P:K: Zn/ N:P:K:S:Mg:Zn:B:Fe/ N:P:K:S:Zn:B)	Geography
Rice	8:15:15:0.5:0.15:0	GB Nagar, Ghaziabad, Rampur, Shahjahanpur, Mainpuri and US Bagar
Wheat	10:18:25:3:0.5:0	Muzaffarnagar, Barielly, Bijnore, Hathras, Pilibhit, Mathura, Meerut and Etah
Maize	14:27:10:4:0.5	Karimnagar, Warangal and Ranga Reddy
Potato	8:16:24:6:0.5:0.15	Agra, Aligarh, Budaun, Bulandshahar and Baghpath
Sugarcane	7:20:18:6:0.5:0	Moradabad, KR Nagar, Farukhabad and Ferozabad
Groundnut	15:15:15:9:0.5:0.2	Andhra Pradesh
Grape, Cotton, Onion, Banana, Tomato, Gourds & Leafy and Vegetable	15:15:15:5:2:0.5:0:0.2	Nasik, Dhule, Jalgaon, Pune, Ahmednagar and Aurangabad

Table 6.
Customized Fertilizer Formulations available for different crops in India (Source: [57]).

as it aids in the provision of optimum use of water, saving money, electricity, and time of the farm. Many researchers reported significant water saving through this technology [61]. The use of sensors with drip and sprinkler irrigation systems can effectively improve the water application efficiency up to 80–90% as compared to the surface irrigation method (40–45%) [62]. In Egypt, potato yields were increased and a loss of 2 billion pounds was recovered in a year through the wireless sensor network technology [63]. Sensors in the prediction of crop nitrogen requirements are also practically significant in agricultural production and environmental safety. Usage of an optical sensor-based algorithm that employs yield prediction and N responsiveness by location can enhance the crop yields and minimize the environmental contamination caused by the application of excessive N fertilizers [64].

2.12 Vertical farming with hydroponics and aeroponics

Vertical farming is a type of indoor farming where the crop grows in multiple levels on a vertical axis which results in maximum production and efficiency per square foot [65]. It is a potential option to achieve sustainability in the agricultural system. By replacing traditional farms with vertical farming techniques, society would be protected both economically and environmentally. It reduces the amount of resources needed and also decreases agriculture's carbon footprint. Hydroponics/aquaponics are nothing but the produced plants in a nutrient-enriched solution in the presence or absence of a growing medium [66]. This system reduces labor, water, and soil efficiently. This system is more sustainable and profitable in food generation; is the future of alternative agriculture [67]. Aeroponics is a subcategory of hydroponics that suspends the roots in the air, thus there is around 95% saving of water than traditional systems [66]. Cultivation of these hydroponics and aeroponics in vertical farming under a controlled environment makes more profitable yields as there will be no damages to the plant by the external factors. By implementing vertical farms in communities, the cost of food would decrease, the economy could thrive, transportation costs are cut dramatically, and therefore so are food prices, create employment and increase educational opportunities. Further, people would be able to become economically and nutritionally stable as it makes a huge impact on both food insecurity and poverty.

3. Programs and policies executed by GOI for sustainable agriculture

The convergence of various policy programs has been initiated by the GOI to ensure the effective utilization of existing resources are briefly discussed here. The National Mission of Sustainable Agriculture (NMSA) under the National Action Plan on Climate Change (NAPCC) was launched in 2010 in order to encourage the judicious management of existing resources. The Paramparagat Krishi Vikas Yojana (PKVY) mission was executed in conjunction with the Indian Council of Agricultural Research (ICAR) and state governments of India to extensively leverage adaptation of climate-smart practices and technologies. In 2015, GOI has launched the Soil Health Card (SHC) scheme to protect the soil health for future agriculture with the main objective of analyzing soil samples of farmers' fields and recommending fertilizers accordingly. Additionally, Neem-Coated Urea (NCU) was introduced to the farmers of India for a slow supplement of nitrogen (N0 by reducing the N losses and excess addition of urea fertilizers. Programs such as the National Project on Organic Farming (NPOF) and National Agroforestry Policy (NAP) was introduced in 2004 and 2014 respectively to encourage the farmers with more profit and ecosystem service through supplements of plant nutrients in the form of organic amendments, improvement of soil carbon storage, and soil protection from erosion loss. States like Andhra Pradesh, Himachal Pradesh, Sikkim, etc. have already adopted and promoted organic farming practices on a wider scale. "Sikkim" state recognized as an "*Organic State*" of India. A "4 per 1000/4 per mille" initiative launched by France in 2015 as a part of the Global Climate Action Plan (GCAA) adopted by the United Nations Framework Convention on Climate Change (UNFCCC) at a conference of the parties (COP) 22 also recognized the importance of SOC in achieving sustainability in agriculture system. It considered the technologies such as agroforestry, conservation agriculture system intensification (CASI), and landscape management to improve SOC.

4. Conclusion and way forward

The post-Green Revolution period witnessed a drastic change in environmental conditions and the status of existing natural resources. A gradual decline in soil fertility has occurred by the non-judicious management of chemical fertilizers that further exacerbated by the progressively decreasing usage of organic amendments. Added to this, abysmally low NUE of applied fertilizers impacted agricultural productivity and sustainability to a great extent. Supplement of plant nutrients in balanced proportion is important; at least in such a way that the critical growth stages of the crop meet the required amount of nutrients results in achieving maximum crop yields that satisfy the growing population. Hence, these constitute a vital component of sustainable food production. Further, agricultural intensification is in critical need of improvements in the flow of plant nutrients to the crops from the soil through efficient nutrient uptake. Improved technologies involved effective nutrient management strategies are the need of the hour to accomplish the targeted food grain production while balancing the stability of the agriculture system, farmers' income, and feed the over-exploiting population of the country.

- Creating awareness among the farmers regarding fertilizer management, nutrient flows, and use efficiencies are essential.
- Strengthening the database on nutrient recommendations specific to soil type, cropping system, and climatic regions is crucial to manage soil productivity.
- Efficient modern technologies are critical in order to ensure the food security of the country.
- Evaluation of technology should be based on locally available resources.
- Identifying policy interventions needed to promote soil management practices that help in achieving maximum crop yields and nutrient use efficiency.
- Developing site-specific holistic land management practices to sustain production rates.
- Implementing a protocol for payment to farmers for strengthening of ecosystem services generated through adoption of sustainable agriculture.
- Bringing sustainability into the agricultural ecosystem needs to be meaningful and result-oriented.

Conflict of interest

The authors declare no conflict of interest.

Abbreviations

%	Percentage
B	Boron
C	Carbon
Ca	Calcium
CASI	Conservation agriculture system intensification
CF	Customized fertilizers
COP	conference of the parties
Cu	Copper
FCO	Fertilizer Control Order
Fe	Iron
GCAP	Global Climate Action Plan
GFSI	Global Food Security Index
GM	Green manure
GOI	Government of India
GR	Green revolution
GVA	Gross value added
ha	Hectare
ICAR	Indian Council of Agricultural Research
INM	Integrated Nutrient Management
K	Potassium
Kg	Kilo gram
Mg	Magnesium

Mn	Manganese
Mt.	Million tons
N	Nitrogen
N_2	Atmospheric Nitrogen
NAP	National Agroforestry Policy
NAPCC	National Action Plan on Climate Change
NCU	Neem-Coated Urea
NMSA	National Mission of Sustainable Agriculture
NPOF	National Project on Organic Farming
NUE	Nutrient Use Efficiency
P	Phosphorus
PKVY	Paramparagat Krishi Vikas Yojana
PSB	Phosphate solubilizing bacteria
S	Sulphur
SHC	Soil Health Card
SOC	Soil organic carbon
SYI	Sustainability yield index
t	Tons
UNFCCC	United Nations Framework Convention on Climate Change
yr.	Year
Zn	Zinc

Author details

Ravinder Juttu[1], Kamalakar Jogula[2], Subhashree Priyadarshini[3], Sharan Bhoopal Reddy[4], Prasanta Kumar Patra[5], Bairi Raju[2], J.D. Saritha[6], Princy Thakur[7], S. Rakesh[7*], Jogarao Poiba[8], A. Krishna Chaitanya[9] and Kiran Pilli[5]

1 Department of Soil Science and Agricultural Chemistry, Regional Sugarcane and Rice Research Station, Professor Jayashankar Telangana State Agricultural University, Nizamabad, India

2 Department of Soil Science and Agricultural Chemistry, Agricultural College, Professor Jayashankar Telangana State Agricultural University, Warangal, Telangana, India

3 Department of Agricultural Entomology, College of Agriculture, Professor Jayashankar Telangana State Agricultural University, Rajendranagar, Telangana, India

4 Department of Soil Science and Agricultural Chemistry, University of Agriculture Sciences, Raichur, Karnataka, India

5 Department of Agricultural Chemistry and Soil Science, Bidhan Chandra Krishi Viswavidyalaya, Nadia, West Bengal, India

6 Department of Soil Science and Agricultural Chemistry, Agricultural College, Professor Jayashankar Telangana State Agricultural University, Palem, Telangana, India

7 Department of Soil Science and Agricultural Chemistry, Uttar Banga Krishi Viswavidyalaya, Coochbehar, West Bengal, India

8 Regional Agricultural Research Station, Visakhapatnam, Andhra Pradesh, India

9 Department of Soil Science and Agricultural Chemistry, Regional Agricultural Research Station, Professor Jayashankar Telangana State Agricultural University, Jagtial, Telangana, India

*Address all correspondence to: rakisavan.940@gmail.com

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Chapter 16

Biostimulants as Plant Growth Stimulators in Modernized Agriculture and Environmental Sustainability

Muhammad Amjad Bashir, Abdur Rehim, Qurat-Ul-Ain Raza, Hafiz Muhammad Ali Raza, Limei Zhai, Hongbin Liu and Hongyuan Wang

Abstract

Plant growth stimulators (growth regulators + biostimulants; PGS) are chemical substances (organic/inorganic), helpful in plant growth and development. These are not considered as the replacement of fertilizers but can help in improved crop and soil quality. Both compounds can amplify the root biomass, nutrients translocation, enzymatic activities, crop yield, physiology, and nutrient uptake. Biostimulants are rich in minerals, vitamins, plant hormones, oligosaccharides, and amino acids. These compounds have a serious role to improve soil health, fertility, sorption, and desorption of nutrients. Hence, have a vital character in nutrients cycling, abiotic stress control, heavy metals bioavailability, and greenhouse gaseous emission. This chapter focuses on the discussions about the influence of plant growth regulators and biostimulants in crop production, soil health, heavy metal cycling, greenhouse gases emission with environmental sustainability. Whereas, the impact of biostimulants on greenhouse gases is a research gap.

Keywords: PGR, Biostimulants, Sustainable agriculture, sustainability

1. Introduction

Modernized agricultural practices are focusing on sustainable environmental systems. The major challenges for agriculture scientists and experts are to improve the crop quality and yield with minimum inputs focusing on environmental sustainability. To fulfill this aim, various breeding programs are introduced but it is a time-consuming and species-specific method. Apart from this, a less time-consuming and cheaper method identification is a vital need, as the use of an organic substance can stimulate healthy plant metabolism and improve their growth and development functions [1].

In addition to increasing population, food security, and environmental pressure, modern agriculture is also facing the challenges of soil degradation and reduction of arable lands. About 24 billion tons of fertile soil has been depleted worldwide due to inadequate agriculture practices and erosion. In addition, drought stress, salinization of cultivated lands, and natural disasters have poorly impacted agriculture. Approximately, 60–70% yield gap is due to abiotic stresses specifically salinity, heat stress, drought, nutrient deficiency, and hypoxia [2].

Biostimulant is a material, which when applied in minute quantity promotes plant growth. Here, the word "minute" describes how the biostimulants are different from soil amendments and nutrients that perform a similar task but are applied in higher amounts [3]. Do not confuse biostimulants with fertilizers because they do not supply nutrients directly to the plants. But facilitate the plant and soil metabolic processes to improve nutrient availability [4]. According to the new regulation (EU, 2019/1009), biostimulant is a fertilizing product that improves the plant's nutritional processes independent of its own nutrient content. Moreover, its goal is to achieve one or more following [2] characteristics of the plant and/or the plant rhizosphere.

i. nutrient use efficiency

ii. tolerance resistance to (a) biotic stress

iii. quality characteristics

iv. availability of confined nutrients in the soil or rhizosphere

Initially, plant biostimulants were used for organic production but as its benefits explored, it is now being adopted in sustainable agricultural practices and integrated cropping systems [2]. Biostimulants are the extracts derived from organic raw substances containing bioactive compounds. The common components of biostimulants are humic substances, mineral elements, amino acids, chitin, chitosan, vitamins, poly-, and oligosaccharides [1]. Biostimulants vary in their formulation and ingredients, but the major classification is on the basis of source and content (includes: hormone-containing products, amino acid-containing products), and humic substances [3].

Various substances such as enzymes, micronutrients, proteins, amino acids, phenols, humic and fulvic acid, salicylic acid, protein hydrolases, and other compounds are sources as biostimulants. Moreover, living organisms i.e., bacteria and fungi that can induce changes among the organism present in plant or soil system are included in the group of biostimulants. Biostimulants are applied via soil application in the forms of granules, powders, capsules, or solutions, or as foliar sprays. Moreover, it can be also applied via fertigation through irrigation systems and foliar application [4]. Different substances are included under the term PGS. **Table 1** summarizes the definition and examples of PGS discussed.

Terminology	Definition	Examples
Biostimulant	It is a fertilizing substance when applied in minute amount improves the plant's growth and nutrition	Seaweed extract, Protein hydrolysates.
Plant growth regulators	It is a synthetic substance that has the potential to improve plant growth and alter biological processes in plants.	Abscisic acid, Cytokinins.
Plant growth hormones	Plant growth regulators when naturally produced by and inside the plant are termed as plant hormones.	-do-

Table 1.
Concept of different plant growth stimulators.

In this chapter, we have focused on the plant growth stimulators (PGS) which comprise both plant biostimulants and growth regulators. The chapter consists of 8 sections, which describes the introduction and significance of the plant growth stimulators (Section 1), the influence of PGS on crop productivity (Section 2), the role of PGS in abiotic stress conditions (Section 3), the efficacy of PGS in soil health (Section 4), the role of PGS in heavy metals cycling (Section 5), its impact on greenhouse gas emission (Section 6), the constraints, challenges and future aspects (Section 7), and the conclusion of the chapter (Section 8), respectively.

2. Influencing the crop productivity with PGS

Plant-derived biostimulants have been reported as an innovative tool to cope with agriculture challenges and environmental sustainability. Moreover, it has been reported that plant biostimulants impact plant growth hormones that improve the plant metabolic activities and ultimately enhance crop productivity [5]. Moreover, it is reported that plant biostimulants improve chlorophyll synthesis, the mineral status, and also synthesis and accumulate antioxidant metabolites. These antioxidants reactivate photosynthetic activity and improve plant growth [2].

Biostimulants are also responsible to increase the leaf chlorophyll content. Its application to vegetables and floriculture crops has been reported to build tolerance against biotic and abiotic stresses by improving the internal and external quality. Moreover, it also reduces the fertilizer requirement thereby is recognized as a step towards environmental sustainability [1, 6]. In addition, biostimulants also enhance the thiamine levels of green beans in proportion to the thiamine content it contains [7]. Furthermore, biostimulants also influence the mechanical properties of fruits and vegetables such as firmness. It might be due to the stiffness of the cell wall that results in extensibility reduction. Biostimulants also significantly improve the cell wall flexibility that helps increase the shelf life of fruits and vegetables, thus facilitate transportation and storage processes [4].

Non-microbial and microbial plant biostimulants also have a positive impact on crop productivity. It increases plant growth and development, nutrient uptake, and translocation consequently increases the yield and biomass production in horticulture and agronomic crops. Moreover, it improves nutrient soil solubilization (both macro and micronutrients), the plant root system architecture, and enhances soil exploration. Thus, it has also been shown to influence nutrient use efficiency specifically nitrogen in plants [2]. Plant biostimulants are also responsible to improve nutrient assimilation by improving the gene expression of functioning in the plant metabolism or due to the improved nutrient uptake and transport [8].

Biostimulants based on chitosan positively impact strawberry pulp firmness and improves the shelf-life by increasing the concentration of the phenolic compound in plants [9]. Moreover, it has been demonstrated that the application of biostimulants in the absence of fertilizers improves the radish shoot and root biomass [6]. Whereas the foliar application of seaweed extract influenced the growth of soybean possibly due to the identified minerals and plant growth regulators present in the biostimulant [10]. Moreover, seaweed is also reported to improve plant water and nutrient use efficiency due to the phytohormones involved. Furthermore, the potential outcomes of seaweed to minimized abiotic stresses and nutrient deficiencies can be expected [11]. Biostimulants have a promising role in improving plant growth, metabolic activities, better stress resistance, and reduction in fertilizer use [12]. Furthermore, **Table 2** summarizes the role of PGS and plants responses respectively.

Crop	PGS	Group	Plant Response	Reference
Zea mays L. (Hydroponics)	Biostimulant	Protein Hydrolysates	Mitigate abiotic stress and regulates the transcription of the gene involved in nitrate transport	[13]
Solanum lycopersicum L.	Biostimulant	Microbe-based	Improve uptake of macro-and microelements (potassium, sodium, and manganese)	[14]
Ocimum basilicum L., *Solanum lycopersicum* L., and *Chrysanthemum indicum* L.	Biostimulant	Vegetable derived protein	Enhances Adventitious Rooting	[5]
Glycine max L.	Biostimulant	Seaweed Extract	Altered the nutraceutical and antioxidative potential and improved the growth and yield	[10]
Crocus sativus L. (Soil less condition)	Biostimulant	Arbuscular mycorrhizal fungi	Increased the polyphenol content	[15]
Lactuca sativa L.	Biostimulant	Amino Acids	Improves the Growth and Yield, Enhance Photosynthetic Assimilation and Nutrient Availability	[16]
Zea mays L.	Biostimulant	Humates and lignosulfonates	Increase root growth, enhance photosynthesis and stimulate N metabolism	[17]
Strawberry tray plants (*Fragaria × ananassa* Duch.)	Biostimulant	10 different biostimulants	Increased pulp firmness, high nutritional value, and yield and fruit quality	[9]
Trifolium pratense L. and *Lolium perenne* L.	Biostimulant (Seed coating)	Soy flour, diatomaceous earth, micronized and concentrated vermicompost	Enhance seedling growth, increased the integrity and compressive strength of seeds.	[18]
Lactuca sativa L.	Biostimulant	Seaweed extract, legume-derived protein hydrolysate and tropical plant extract	Increase leafy vegetable productivity in low fertility soils, better physiological and biochemical status	[19]
Raphanus sativus L.	Biostimulant	Biostimulant, Vitamin B12, and CoQ10	Improved root and shoot biomass	[6]

Table 2.
Plant growth stimulators and plant responses in different crops.

3. Limiting the abiotic stress by PGS

Plants face multiple stressful events throughout their lifecycle. Stresses are classified based on the nature of the trigger factor as biotic and abiotic stresses. Biotic stresses are caused by a living organism such as insects microorganisms, weeds, etc. that impact plant growth, and productivity. However, the latter one is general associated with different environmental components that negatively impact plant development and survival. Drought, non-optimal temperatures, low soil fertility, and salinity are the most common abiotic stresses that limit agriculture production globally. Whereas, in the developing countries where the life of the majority depends on the agriculture sector, drought and nutrient deficiencies major issues [20].

Besides this, the rapid increase in population leading to urbanization and increases soil erosion has poorly impacted the prime cropland. Therefore, it is the need for time to utilize the less productive soils and enhance the crop yield and productivity [16]. Biostimulants ensure a promising role to improve the productivity of vegetables and also develop tolerance against stresses. Moreover, it positively impacts the plant metabolic activities in optimal and sub-optimal environmental conditions. In addition, it is very crucial to identify the proper timing for the application of biostimulants. It depends on the critical stages of development and crop species. To avoid unexpected results, minimize production cost and wastage of products, it is good to determine the exact dose and application time of biostimulants [20].

Diverse changes in temperature and precipitation have been reported due to climate change, this has resulted in severe drought conditions [16]. Drought has adverse effects on the plant gas exchange and causes changes in transpiration and photosynthetic rates, which ultimately results in yield losses. Biostimulants can be used to overcome water stress as it is effective to improve water use efficiency in plants [20]. It is reported that the micro-algal-biostimulants minimized the drought damaging effects on tomatoes and improve plant growth. It might be due to the presence of plant growth hormones, like abscisic acid that regulates transpiration and reduce water losses, present in biostimulant [21]. Microalgae improve the total flavonoid and phenolic content in plants which also increase the enzymatic activities of antioxidants such as catalase, superoxide dismutase, ascorbate peroxidase that consequently mitigate drought-induced oxidative damage [22].

Furthermore, biostimulants are also useful against nutrient deficiency. The results have shown that the application of biostimulants cannot replace fertilizers but it can contribute to overcoming nutrient deficiency and imbalanced conditions. It is responsible for improving plant root morphology which ultimately improves nutrient uptake, translocation, and assimilation [23]. Cold stress or low temperatures adversely affect plant metabolism and delay physiological processes. It also damages the cell membrane by destabilizing phospholipid layers. Biostimulants also help to stimulate biosynthetic pathways that increase the osmotic molecule accumulation, membrane thermostability, and overcome chilling injury. Moreover, the seed priming with chitosan also improved germination and plant growth under temperature stress [24].

The most abundant environmental stress is a salinity that adversely impacts plant metabolism and growth. With the application of biostimulants to salt stress environmental conditions, the damage can be minimized as it induces the accumulation of osmolytes to increase the osmotic potential of plant cells and enhance the level of protective molecules against oxidative stress [25]. Moreover, it has been reported that the protein hydrolysates-based biostimulant significantly mitigates single as well as multiple stresses (nutrient stress + hypoxia or nutrient stress + salinity) in maize under hydroponic conditions [2].

Plant growth regulators also play a constructive role to mitigate the abiotic stress damages and improve plant development. Such as, salicylic acid is effective against drought as it increases the restoration process in plants. Moreover, putrescine fights against oxidative, drought, and salinity stress probably due to its acid-neutralizing abilities. Thus, plant growth regulators, plant growth-promoting rhizobacteria, and biostimulants could play a significant performance against environmental stresses [16].

4. Efficacy of PGS in soil health

Plant growth regulators also effectively influence the soil properties and ultimately give a huge benefit to agriculture management. As describes earlier, plant biostimulants improve nutrient availability, uptake, translocation, and assimilation, which is beneficial to organic farming. In addition, incredible results can be obtained with the integrated application of biostimulants with chemical fertilizers in soil [26]. It contributes to improving the cation exchange capacity of the soil and enhances the solubility of the nutrients in soil solution which subsequently increases the nutrient availability for plant uptake [8]. Whereas, biostimulants are not nutrients and has no direct impact on nutrients bioavailability but they have a potential to reduce the application of mineral nutrients [6].

Protein hydrolysates, an important plant biostimulant is prepared using protein sources by the process of partial hydrolysis. It comprises amino acids, mixtures of poly- peptides, and oligopeptides. When applied as foliar spray or in the soil/root system, protein hydrolysates improve the microbial biomass and activity, soil respiration by providing a rich source of C and N to microbes. Moreover, it forms complexes and chelates with soil micronutrients (i.e., Zn, Mn, Fe, and Cu), improves nutrient availability, and ultimately improves plant nutritional status [8].

Another well-known plant biostimulant is "seaweed extracts". Due to its complex biochemical composition (minerals, antioxidants, polysaccharides, hormones, vitamins, pigments, fats, oils, acids), it is highly difficult to understand its mechanism. Likewise, protein hydrolysates, seaweed extract can be applied to soil as well as plants (foliar spray). It is responsible for improving soil retention, soil microflora as well as soil remediation. Moreover, it can be a rich source of nutrients and probably have hormonal effects. Whereas, multidisciplinary approaches are required to understand the complex interaction between bioactive compounds present in the extract [11].

5. Role of PGS in heavy metals cycling

The increase in anthropogenic activities including industrial and mining activities, urbanization, use of chemicals in agriculture has potentially increased the concentration of toxic elements in soil throughout the globe [27]. Moreover, wastewater mishandling also contributes to heavy metal contamination and induces toxic effects on plant metabolic activities, soil environment, groundwater, and ultimately human health [28]. One of the most toxic trace elements is chromium (Cr). It is harmful to the soil microbes as it depresses their microbial and enzymatic activities, as well as humans if enters the food chain [29]. Therefore, it is important to minimize or treat the negative impacts of Cr. Plant growth stimulators can also play a significant role in this regard.

The application of micronutrient-amino acid is responsible to reduce the Cr stress in plants. It is reported that iron-lysine (Felys) application significantly improved plant growth and biomass. Additionally, with the increased nutrient uptake, gaseous exchange parameters also increased whereas it contributes to form complexes that reduce oxidative stress in plants. Therefore, the Cr toxicity caused due to contaminated water can be treated using Felys. Whereas, the mechanism behind the Felys attributes needs to be explored [30].

The foliar application of Zinc-lysine (Znlys) also improved rice growth and contributed to stimulating the anti-oxidant defense system, decrease oxidative stress, increase Zinc (Zn) uptake, and decreases Cr concentration in plants. Whereas, further studies are required to explore the mechanism of Znlys in mitigating Cr level in plants [31]. Moreover, Znlys is also effective to reduce cadmium (Cd) concentration in wheat along with improving Zn contents and plant growth in Zn deficient and Cd contaminated soil. It is useful to protect people from Cd risk and Zn deficiency [32].

Apart from biostimulants, plant growth regulators also contribute to phytoremediation. Plant growth regulators can be defined as the substance that can impact plant growth and is capable of altering biological processes in plants. Such compounds when produced inside the plant are known as plant hormones but when used as synthetic compounds to play a similar role are termed as plant growth regulators [33]. Auxins perform various biochemical changes in plant cells and their membranes which reduces the toxicity of metal ions [34]. Different hypotheses report that auxins cause changes in the cell membrane and alter its properties against toxic elements [33]. It also improves the rate of transpiration and ultimately heavy metal adsorption.

The use of cytokinins on *Alyssum murale* also improves the plant aerial biomass and transpiration due to the adsorption of heavy metals in soil solution. Likewise, the application of cytokinin on *Helianthus annuus* is helpful in the adsorption of Zn and lead (Pb). Studies reported that the usage of salicylic acid helps reduce the negative impacts of copper (Cu) and Pb in plants. Thus the use of plant growth stimulators is significant in heavy metal recycling [33].

6. Greenhouse gases emission and PGS

Greenhouse gases (GHGs) are defined as the gases that obtain heat energy from the sunlight and limit the backward movement of radiations from the earth's crust thus resulting in global warming. The agriculture sector contributes a lot in this aspect by the emission of methane (CH4), nitrous oxide (N_2O), and carbon dioxide (CO_2). One of the major sources of GHGs emissions is paddy systems [35]. Moreover, the long-term application of manures also increases GHGs emissions [36].

With the increase in population, the demand for food has also increased. To fulfill this challenge, the farmers tend to apply more fertilizer to attain more yield. However, field fertilization is supposed to be a major source of GHGs emissions. It is reported that agriculture produces about 90% N_2O and 20% CO_2 worldwide. Depending upon the global warming potential, carbon dioxide and nitrous oxide are two important GHGs. Moreover, after CH_4, and CO_2, N_2O is an important GHG that contributes about 6–8% of global warming [36]. Therefore, it is the need of today to introduce such agriculture practices that ensure high yield with minimum negative impacts on global warming and climate change.

Microbes-biostimulants specifically N-fixing microorganisms are responsible to increase N_2O emission. Whereas few pieces of research have been reported in this regard. Further studies need to be conducted to explore the impacts of different types of biostimulants on agro-ecosystems [37]. Additionally, the foliar application of plant growth regulators (abscisic acid and kinetin) has been shown to mitigate the N_2O emission and also manipulate plant growth and development processes in the wheat cropping system. It is possibly due to the manipulation of anatomical and physiological processes. Thus, the application of plant growth regulators might be an effective tool for modernized agriculture and environmental sustainability [38]. Apart from this, there is a huge gap to study PGS for GHG emission and reduced agro-environmental pollution, especially from non-point sources.

7. Constraints, challenges, and future aspects

Agriculture production is facing multiple challenges including food security, climate change, soil restoration, and environmental sustainability. Plant growth stimulators have the potential to overcome the biotic and abiotic stresses, improve crop productivity, better soil nutrient cycling, mitigation of heavy metal uptake, and GHGs emission. Due to the complex composition of biostimulants, their potential role and mechanism are still not clear. Therefore, further studies about the possible use of biostimulants to minimize GHGs emission needs to be studied.

Biostimulants are also expected to increase NUE, therefore, careful monitoring, climatic aspects, and related modeling need to be studied. Limited literature related to the impacts of biostimulants under sub-optimal nitrogen regimens is available. Further studies can bring huge benefits to modern agriculture. Moreover, open field studies should also be carried out in the future, which then moves back to the lab for further elucidation. Few field-based research using biostimulants has been reported which is a major constraint to adopt its application in farming. Furthermore, the farming community should be introduced with the product along with the cost–benefit analysis, thus moving towards environment sustainability.

Currently, biostimulants are gaining popularity in the market. Variety of biostimulants with different active ingredients (humic substances, seaweed extracts, microbial amendments, and amino acids) are estimated to account for \$2.6 billion and will reach about \$5 billion by 2025 [2]. Therefore, it is time to introduce new and beneficial biostimulants that have practical application and yield benefits for sustainable agriculture. Integration of plant biostimulants and growth regulators with nutrients and waste organics for different regions can be introduced with also helps in minimizing pollution and waste recycling.

8. Conclusion

A sustainable agriculture management system needs to be adopted for dealing the adverse climatic conditions. Plant growth stimulators have positively contributed towards modern agriculture and have the potential to improve crop yield, plant growth, and development, handle biotic and abiotic stresses, minimize heavy metal translocation, and contribute to mitigating GHGs emissions. Biostimulants are rich in multi-nutrients but cannot replace fertilizers. Although it has a potential to improve soil quality and plant productivity even under stress conditions. Whereas, few researches regarding GHGs emission using biostimulants has been reported. It is a huge research gap. Whereas, different mechanisms need to be studied further to develop a better understanding and introducing useful products.

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Author details

Muhammad Amjad Bashir[1,2], Abdur Rehim[1*], Qurat-Ul-Ain Raza[1], Hafiz Muhammad Ali Raza[1], Limei Zhai[2], Hongbin Liu[2] and Hongyuan Wang[2*]

1 Department of Soil Science, Bahauddin Zakariya University, Multan, Pakistan

2 Key Laboratory of Nonpoint Source Pollution Control, Ministry of Agriculture, Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, P.R. China

*Address all correspondence to: abdur.rehim@bzu.edu.pk and wanghongyuan@caas.cn

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Chapter 17

Role of Nanoparticles in Abiotic Stress

Mohd. Tariq, Shipra Choudhary, Harjeet Singh, Mohd. Asif Siddiqui, Hirdesh Kumar, Asad Amir and Neelesh Kapoor

Abstract

Nanotechnology is currently seeking much attention of researchers because of their wide applications in diverse sectors including agriculture. The influence of nanoparticles on physiological state of plants at the different levels of their organization, beginning from molecular, has been studied at various plants. It is known that nanoparticles in different concentrations can impact both positive and negative biological effects. Nanomaterials confer profound uses for sustainable crop production, reducing loss of nutrients, suppression of diseases and thereby enhancing the yields. Concerning the role of nanomaterials in alleviating the damage of plant abiotic stresses or in inhibiting plant growth and its toxicity, further studies are essential under different levels including plant molecular and cellular levels. A wide variety of research has been conducted to study plant responses to waterlogging stress that include various disciplines like molecular, biochemical, and physiological, anatomical and morphological examinations. Nano technological implications for curbing water-logged conditions recently came into limelight and have drawn much attention in the last few years. Nanotechnology is defined as the systems and processes which operate at a scale of 100 nm or less. Nanotechnology has many applications in the field of agriculture. There are majority of nano-materials which are known for its plant growth promoting effects. Nanoparticles have unique physiochemical properties such as high reactivity, particle morphology, and large surface area. They also boost the plant metabolism.

Keywords: abiotic stress, crop plants, heat stress, heavy metals, nanoparticles, salinity

1. Introduction

Population explosion during the last few decades has led to increased pressure on the agriculture sector by an upsurge of continuously increasing food demand. Natural resources of the world are continuously diminishing at a much faster pace than their renewal and the agriculture sector is no exception to this presently prevailing scenario. Sustainability issues due to population explosion, climate change, urbanization, habitat loss assisted by environmental issues are some of the global challenges faced by the green plants including the agriculture sector [1]. Plants, the vital component of our planet remain always exposed to different environmental variations and numerous stress factors throughout their life. Unlike animals, plants are deprived of motility to a better place on the arrival of any kind of stress either *biotic* or *abiotic*. To combat such stresses, nature has provided these living entities with certain defensive mechanisms that help these sessile organisms to endure these unpleasant situations. Though plants develop several mechanisms which involve avoidance, escapism, and tolerance, to deal against adverse conditions their responses could vary appreciably even in the same plant species. For this reason, the identification of tolerant plant species is always the major concern towards sustainable agriculture and crop production [2]. Major abiotic stresses which affect plants include *heat, salinity, cold drought, flooding/submergence (anoxia), chemical toxicities*, and *excess light* [3].

Technological advancements in the last few decades have led to profound structural changes in the agriculture sector and improvisation of plant health dealing with different *abiotic* stresses, improvements required to increase the production rate in ways that promote food security and public health improvement remains the matter of concern. So, there is a major concern among scientific communities to raise world food crop production by 70% [4]. In such varying environmental scenarios, it is needful to recognize an area of research to conquer the technical challenges in addressing the yield barrier, resource use efficiency, and development of environmentally accepted technology [5].

Nanotechnology and nano-sciences have come out as powerful and promising tool dealing with nearly all the aspects of the masses and people's life in 21st century that include medicine, agriculture, industrial, environment, electronics with application in numerous preparations [6, 7]. Precise potential to control and fabricate matters at nano-scale remain the beauty of this newly emerging scientific discipline. Nanotechnology has emerged out broadly into the '*agri-food sector*' which include the nanosensors, tracking devices, targeted delivery of required components, food safety, new product developments, precision processing, smart packaging, and others [8–11]. Nanotechnology offers a wide research area and provides possibilities for a large scope of diverse applications and advantages in fields of biotechnology and agriculture-based research such as disease prevention [12], nutrient management by nano-fertilizers [13], nano-pesticides or nano-herbicides [14, 15], mitigating abiotic stress [2]. Also, nanotechnology holds good promises for solving the problem associated with abiotic stresses to obtain sustainability in the field of agriculture [2].

Improving plant traits against different diseases and abiotic and biotic stresses such as drought, salinity, plant diseases, and others is one of the primary objectives of biotechnological research. Nanotechnology-enabled gene sequencing is expected to introduce rapid and cost-effective capability within a decade [16], thereby leading to more effective identification and usage of plant gene trait resources that could help plants in overcoming adversities due to different abiotic stresses. Considering these issues in this article, we are dealing with how nanotechnology can be made useful for mitigating various abiotic stresses of crops and various mechanisms associated with them [1].

2. Abiotic stress in crops and current scenario

Plants are constantly exposed to various stress factors throughout their life span. As per the data available, the relative decreases in potential maximum yields associated with abiotic stress factors vary between 54 and 82% [17]. Crops confront various types of abiotic stress and it has been well documented as well that among stresses, extreme temperatures (freezing, cold, heat), water availability (drought, flooding), and ion toxicity (salinity, heavy metals) are the major causes which adversely affect the plant growth and productivity worldwide [18–21]. These abiotic stresses are interconnected to osmotic stress that results in the disruption of ion

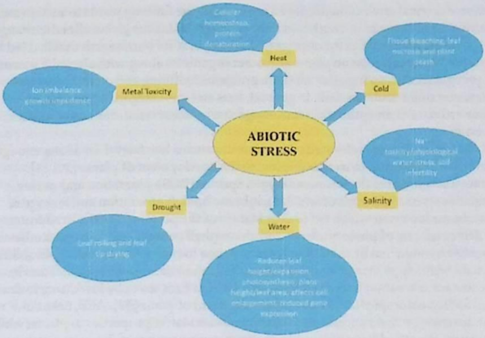

Figure 1.
Types of abiotic stress with their effects on growth of plants.

distribution and cell homeostasis. Crop plants are adversely affected by abiotic stress conditions. On account of the current scenario, more than about 50% loss of yield/year is sole because of abiotic stresses such as drought, salinity, heat, and cold. In developing countries, drought and low soil fertility has been proved to be a major cause for affecting crop production [22]. Recently, several transcription factors (TFs) due to their efficacy as a master regulator, have been proving as a potential candidate for genetic engineering to bread stress-tolerant crops and improve stress tolerance [23]. Six Asian region countries namely Bangladesh, China, India, Indonesia, Pakistan, and Thailand are actively involved in the Research and Development related activities for the development of abiotic stress-tolerant crops [24]. Various abiotic factors along with their probable significance are depicted in **Figure 1**.

3. Role of nanotechnology in abiotic stress

Nanotechnology is a platform for developing tools and technology for the improvement of the bio system [25]. Nanoparticles (NPs) are small molecular aggregates with dimensions of 1-100 nm [26]. NPs have been investigated to improve plant growth, development, and productivity and thus, proving their use to overcome various abiotic and biotic stress of crops [27]. In the last decade, the science of nanotechnology has attained, a promising position to mitigate the constraints associated with the aforementioned stresses to achieve a secure future of agriculture worldwide and nano technological findings possess immense potential to open up numerous ways in the field of biotechnology and agriculture [28, 29]. Some of them are discussed here in detail:

3.1 Heat stress

The negative impacts of heat stress (also Thermal stress) on plants are substantial, detrimental, and often account for reduced crop yield and productivity as well.

Adverse thermal environments pose a great challenge for crop plants to sustain and survive. In addition to it, another major concern remains the global climatic change i.e , an overall increase in the average global temperature of the earth that had led to increased thermal stress on plants and other organisms along with altered patterns of precipitation. Leaving aside all these problems, defining and quantifying heat stress remains a daunting task. In general, heat stress is categorized relative to some estimate of an optimal thermal range that is characteristic of each species in question.

Heat stress involves elevated temperature at such a harsh level for a long enough time that could result in irreparable loss to the development of plants [30, 31]. Heat stress enhances the Reactive Oxygen Species (ROS) generation and causes oxidative stress, as a result of which membrane lipid degeneration and leakage of membrane ion occur which led to degradation of the protein [32–35], in addition to decreased rate of photosynthesis and chlorophyll content [36]. Several studies have been conducted by many workers from time to time to access the applicability of nanotechnology to minimize heat stress. Selenium nanoparticle application in the low concentration found reducing the effect of heat stress by increasing hydration ability, chlorophyll content, and development of plant [37]. Also, Selenium nanoparticles at low concentrations exhibit antioxidative properties to plants, while oxidative stress had been induced by the high concentration of Se nanoparticles [38, 39]. Plants synthesize several heat shock proteins and molecular chaperones during the period of heat stress [40]. Other proteins are assisted by heat shock proteins in sustaining their fidelity in stress conditions [30] and are involved in heat stress resistance. It was already in reports that multiwall carbon nanotubes could upregulate gene expression of heat shock proteins *viz.* HSP90 [41]. Also, maize plants exposed to CeO2 nanoparticles depicted excessive generation of H2O2 and upregulation of HSP70 [42]. Furthermore, TiO2 nanoparticles treatment reduced the effect of heat stress by stomatal opening regulation [43].

3.2 Salinity

Salinity, a major type of abiotic stress factor, limits the production of food and deteriorates the quality of ever-increasing growth in food crops. For scientific communities, increased salinity remains a major constraint to attain sustainable crop production. Worldwide, 20% of cultivated land is facing salinity stress and the amount is increasing day by day. The majority of crop plants species belong to the category of glycophytes, which are highly susceptible to salt stress hence are the most critical environmental abiotic stress that can ruin crop production [44, 45]. Most salinity problems arise due to excess sodium chloride (NaCl) which is widely distributed along with coastal and arid region soils and water supplies. Higher levels of NaCl impose at least three types of problems for higher plants. These include: (i) the osmotic pressure in the external solution can exceed the osmotic pressure in the plant cells and therefore require an osmotic adjustment by the cells to avoid desiccation; (ii) sodium, in excess, can disrupt the uptake and transport of nutritional ions such as K and Ca; and (iii) both Na and Cl can exert direct toxic effects on membranes and enzyme systems [46]. Besides the aforementioned problems, lowering of soil osmotic potential, creation of nutritional imbalance, enhancing specific ionic toxicity (salt stress), or one or more combination of these factors, are some of the common implications that salinity stress exerts on crop plants. Most vital processes of plants like photosynthesis, protein synthesis, and lipid metabolisms, etc. are badly affected by salinity stress [47]. Salt stress is associated with oxidative stress too. However, to confront salt stress-induced oxidative stress, plants are very well equipped with a defense system of various antioxidant enzymes that include superoxide dismutase (SOD) and peroxidase (POD). The SOD constitutes the first line of defense against ROS [48] and dismutase superoxide radicals to H2O2, whereas POD reorganizes H2O2 into water and oxygen [49]. Besides oxidative stress, salt stress also creates osmotic stress, which reduces the ability of plants to take up water and minerals [50]. Also, plants have been found to abide by osmotic stress by the provision of accumulation of osmolytes, such as proline (Pro) and Glycine Betaine (GB) [51]. Application of nano-fertilizers is a quite hopeful method that can potentially increase plant resource use efficiency and help in reducing environmental toxicity due to the accumulation of unused chemical fertilizers and pesticides in the soil. Therefore, the application of nano-fertilizers could serve as an alternative approach to overcome soil toxicity issues and other associated stresses.

Adverse effects of salinity stress on crop plants have been extensively studied by many workers from time to time. Hussein and Abou-Baker [52] conducted experiments to study the foliar application of nano zinc to mitigate the adverse effect of salinity and confirmed that diluted seawater could be used in the irrigation of the cotton plant. They reported that increasing the application rate of nano-Zn may reduce phosphorous (P) absorption and translocation to leaves and consequently reduce the P/Zn ratio. They suggested that an additional dose of P-fertilizer with nano-Zn could be used to avoid the P/Zn imbalance. Avestan et al., [53] in their investigations proposed that salinity stress treatments were detrimental to morphological and physiological parameters of strawberry plants. They found that nSiO2 treatments suppressed the negative effects of salinity, possibly by improving the Epicuticular Wax Layer (EWL); and nSiO2 treatments enabled salt-stressed plants to better maintain their chlorophyll content and leaf relative water content (RWC) and relative water protection (RWP) relative to controls (no SiO2). They concluded their findings by suggesting three possible directions for future research: (1) Further exploring how variation in the timing of silicon treatments influences EWL deposition by testing EWL at multiple plant developmental stages; (2) investigation of whether there is genetic variation for EWL deposition in strawberry; and (3) testing to distinguish the benefit of greater EWL deposition in saline conditions relative to the benefit of the other signaling and physiological changes that are linked to increased silicon uptake.

Khan [54] in his studies investigated the effect of nano TiO2 in several plant developmental processes including defense against environmental stresses. They concluded that the cumulative effect of the parameters under consideration contributed to improved growth and yield of tomato plants. Therefore, based on the assessment of results it was propounded that nano-TiO2 at the rate of 20 mg/l proved best in enhancing the growth, yield, and quality of tomatoes. In one more study, conducted by Yassen et al., [55] on the cucumber (*Cucumis sativa*) effect of silicon dioxide nanoparticles was assessed where the results indicated an increase in nitrogen and phosphorus, content and uptake and decrease in Na content and uptake when adding SiO2 nano fertilizer. The findings of the study suggested that silicon dioxide nano fertilizer can exert a positive effect on the growth and yield of cucumber.

3.3 Heavy metal stress

Nano biotechnology growing as a technology that could make the environment cleans. Nanoparticles, often regarded as particles having a significant amount of surface area with unique physical and chemical properties and having applications in reducing the negative effects of heavy metals on the natural wealth [56, 57]. Some workers have exploited nanotechnology to explore plant phytotoxicity caused by heavy metals in various environments. Although nanoparticles are cost-effective in reducing heavy metal toxicity in plants [58], mitigation of heavy metal-induced root growth inhibition and oxidative stress in the plant has been barely studied [58, 59].

Heavy metal ions were productively adsorbed by magnetic nanoparticles ($Fe3O4$) [57]. In addition, Nanoscale zero-valent iron (nZVI) nanomaterials are core-shell structures that are in use for decreasing metal toxicity. Ronavari et al. [60] reported that nZVI nanoparticles are for immobilizing heavy metal ions due to their distinct structure. Also, Fajardo et al. [61] found that lead and zinc mobility and availability decreased when soils were treated with nZVI. The addition of nZVI and active carbon efficiently immobilized copper, lead, cadmium, and chromium in sediments, thus, decreasing the bioavailability and toxicity of heavy metals [62].

Nano hydroxyapatite (nHAp) particles are also in use to remediate metal toxicity. nHAp have been successfully applied to remediate soils contaminated by metals and to purify wastewater due to their outstanding ability to absorb heavy metals like copper (II), zinc (II), lead (II), and cadmium (II) [63]. Zhang et al. [64] found that nHAp effectively decreased the exchangeable fractions of Pb and Cd in contaminated sediments, especially for Pb, and dramatically decreased the metal(loid) ion concentration in pore water.

Carbon nanotubes (CNTs) were discovered by [65] and can be used as absorbents. They can be (i) single-walled carbon nanotubes (SWCNTs) and (ii) multi-walled carbon nanotubes (MWCNTs) [66, 67] and are promising nanomaterial to remove organic and inorganic toxic compounds [68, 69].

3.4 Drought stress

Plants have been always combating water stress for millions of years, ever since they first left the water bodies and conquered and colonized dry land. When drought strikes, higher plants are the first victims that have always been obliged to endure it or to adjust their life cycles to avoid it. Thus, a major means of propulsion behind the evolution and emergence of land plants has been their need to search for water, to absorb it, to transport it, and retain it. Even so, drought is still the major constraint to crop production [46, 70, 71]. The term '*Drought*' does not merely represent lack of rainfall instead for plant physiologists, it is a concurrence of various environmental stresses that includes: (i) low soil moisture availability; (ii) high evaporative load, (iii) high temperature, (iv) high solar irradiance, (v) increased soil hardness, (vi) unavailability of nutrients and (vii) accumulation of salts in the topsoil region.

Taran et al., [72], in their studies have shown that Cu-Zn-nanoparticles reduced the negative effect of drought action upon plants of steppe ecotype Acveduc. In particular, increased activity of antioxidative enzymes reduced the level of accumulation of Thiobarbituric Acid Reactive Substances (TBARS) and stabilized the content of photosynthetic pigments, and increased relative water content in leaves. Colloidal solution of Cu-Zn-nanoparticles had a less significant influence on these indexes in seedlings of the *Stolichna* variety under drought. They studied the use of binary compositions of nanoparticles in agro-technologies to enhance the biological productivity of agriculture systems. Ashkavand et al., [73] studied the effect of SiO_2 nanoparticles on drought resistance in hawthorn seedlings and concluded that silicon nanoparticles (SNPs) can increase plant resistance to drought stress. It could be explained by the improvement of photosynthesis rate and stomatal conductance by SNPs pretreatments. Application of silicon on two sorghums (*Sorghum bicolor* (L.) Moench) cultivars possessing different drought susceptibility exhibited improved drought tolerance irrespective of their drought susceptibility by lowering shoot to root (S/R) ratio, which perhaps could be an indicator of improved root growth and the maintenance of the photosynthetic rate. These findings could be attributed to improving the drought tolerance of sorghum via the augmenting water uptake efficiency of plants [2, 74]. Applications of silver nanoparticles

(AgNPs) has also been appreciated in diminishing negative effects of drought stress on lentil (*Lens culinaris* Medic). Significant effects of different concentrations of Polyethylene glycol (PEG) and silver nanoparticles on germination rate and germination percentage, root length, root fresh, and dry weight in lentil seeds were reported [75]. In a study, conducted by Sedghi et.al [76], it was observed that nano zinc oxide has the potential to enhance seed germination percentage thereby, overcoming water stress.

3.5 Water logging

Over irrigation, prolonged periods of precipitation coupled with poor soil drainage system gives rise to a condition called *'water logging'*. Both, natural vegetation and agriculture crops are equally affected by this worldwide occurring condition of waterlogging. The waterlogged soils offers/presents an unpleasant and uneasy environment for normal growth and development of plants because: (i) air spaces occupied by water delays the exchange and diffusion of gases between the roots (rhizosphere) and atmosphere [77]; (ii) levels of dissolved oxygen are depleted from soil solution by respiration of soil inhabitants and roots [78] and (iii) flooding of fields is often associated with the release of toxic compounds and obnoxious gases. Depending upon the height of the water column produced, flooding can be classified as (i) *waterlogging*, when it is superficial and encase only the roots, and (ii) *submergence*, when water completely covers the aerial plant tissues [79]. In both types of flooding, the movement of oxygen from the air to plant tissues is highly disrupted [80], producing a natural condition known as hypoxia (<21% O2) [79].

Depending upon certain parameters like temperature, microbial respiration activity, frequency, and duration of soil saturation, the depletion of dissolved oxygen in waterlogged soils leads to conditions called *'hypoxia* 'and *'anoxia'* within few hours to days. In recent years, flooding stress and its subordinates like submergence, waterlogging, hypoxia, and anoxia, were investigated extensively in plants, especially in *Arabidopsis* and rice, to pinpoint molecular elements that may play a vital role in flood tolerance. Roots of the plants remain the first victims that are worst hit by flooding. Plant roots facing waterlogging stress follow glucose metabolism according to the classical scheme of alcoholic fermentation in an oxygen deficit medium *(anaerobiosis)*, where self-poisoning of tissues takes place as a result of the formation of end products of fermentation mainly ethanol. Maintenance of an appropriate oxygen supply and energy balance is paramount for the survival of the root system to waterlogging stress.

Nanotechnology has provided new discernment to the problems arising in plants and food science (post-harvest products) and offers novel approaches to the rational selection of raw materials. Silver Nano Particles (SNPs) are the most commonly used nanomaterials in the field of nanotechnology after carbon nano-tubes that every day is added in its application to the nano-world. In this sense, nanoparticles are useful tools as an excessive water supply induces hypoxia in plants [80], increases the vulnerability to pathogen attack [81], and limits the flow of light to the plant [82].

During recovery after a flooding event, plants experience oxidative stress [83] and must remobilize nutrients to achieve a normal homeostatic state [84]. Concerning the protection of plants against oxidative stress, nanomaterials are found to mimic the role of first-line defense antioxidative enzymes like peroxidase, superoxide dismutase, and catalase, which are supposed to form the antioxidant defense grid [85]. Also, plants respond to flooding and the associated stress by changes in gene expression that are finely regulated at a multilevel scale from epigenetics [86] to transcriptional [80, 87] and translational regulation [88].

Rezvani et al., [89] conducted experiments to study the effect of Nano silver ions (as an ethylene inhibitor on the growth of Saffron (*Crocus sativus*) under flooding conditions. Corms of saffron were soaked with different concentrations of nano-silver ranging from 0 to 120 ppm (0, 40, 80, and 120) and planted under flooding stress or non-flooding stress conditions and the results of the investigations showed that the number of roots, root length, fresh and dry weight of roots and leaves were reduced by 10-day flooding stress. Soaking the saffron corms with 40 or 80 ppm concentration of Nano silver rewarded the effect of flooding stress on the root number by increasing it. Also, it was found that 40 ppm of nano-silver increased the root length in stress. 80 ppm concentration of nano-silver was found to increase leaves dry weight. In another study conducted on the same plant (*C. sativus*) under flooding stress, foliar application of Nano silver was accessed by Sorooshzadeh *et al.*, [90]. Results of the investigations showed that flooding stress led to a significant reduction in weight and height of the plant and the number of corms per plant was increased by increasing the concentration of nano-silver. In all, they concluded that flooding stress and Nano silver had a significant interaction effect on all parameters under consideration of the study.

4. Mechanism of abiotic stress control by nanoparticles (NPs)

Developing technology for improving food production, minimizing crop productivity loss is the prerequisite for obtaining sustainability in the field of agriculture. Abiotic stress of plants is considered a major emerging problem in the field of agriculture, its diverse types include salinity drought, waterlogging, submergence, heavy metal stresses, and mineral and metal toxicity/deficiencies that minimize crop growth and productivity [91–93]. A decrease in productivity is mainly attributed to these factors. Plant throughout their lifespan has to face various types of abiotic stress and has to come up with strong defense mechanisms to cope up with them. Investigation on NPs has reported that they help plants to overcome abiotic stress by their concentration-dependent impact on plant growth and development [73, 94–96]. It is also reported that various antioxidant enzymes like catalase (CAT), peroxidase (POD), superoxide dismutase (SOD) were found to enhance their activity using NPs [97]. Depending upon their chemical composition, size,

Figure 2.
Various nanoparticles with their effect on plant growth.

surface covering, reactivity, NPs interact with plants in various ways causing many morphological and physiological changes and play a very vital role in improving crop plants. NPs has both positive and negative effect on plant growth and development [98]. Some NPs along with their possible effect (negative and positive) on a plant are depicted in **Figure 2.**

5. Conclusion

Nanotechnology, a multi-disciplinary approach, has emerged out as a powerful discipline in the last few years and is revolutionizing various fields like medicine, agriculture, industrial, environment, electronics, etc. Nanotechnology is emerging as a tool for agriculture by empowering it with tools to conquer nutritional poverty and food scarcity. Nanoparticles are proven beneficial to boost plant growth, development, and increase yield capacity and help to overcome biotic and abiotic stress. The use of nanotechnology will lay a strong platform and will permit a secure future towards sustainability, crop productivity, and overcome abiotic stresses, where loss can be minimized and yield could be enhanced. The most effective way for understanding the action of the mechanisms of NPs applications is to apply the present knowledge by collaborating with various disciplines that may include molecular biology, plant physiology, plant breeding, cytology, soil physics along nanotechnology. Such associations could be helpful for the encouragement of multi-disciplinary projects that may be carried worldwide. Nanotechnology promises new insights into the mechanism of various abiotic stress tolerance in plants to complement physiological studies. Also, there is a need to detangle various factors responsible for abiotic stress. The implementation of action mechanisms of NPs will require information and expertise from the aforementioned disciplines to combat various stress effects. The applicability of nanotechnology needs to be commercialized from laboratory to agricultural fields.

Author details

Mohd. Tariq[1,2†*], Shipra Choudhary[2†], Harjeet Singh[3†], Mohd. Asif Siddiqui[2], Hirdesh Kumar[2], Asad Amir[2] and Neelesh Kapoor[4]

1 G. B. Pant National Institute of Himalayan Environment, Almora, Uttarakhand, India

2 Department of Biotechnology and Microbiology, Meerut Institute of Engineering and Technology, Meerut, Uttar Pradesh, India

3 Cattle Genetics and Breeding Laboratory, Central Institute for Research on Cattle, Meerut, Uttar Pradesh, India

4 Department of Fingerprinting, College of Biotechnology, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh, India

*Address all correspondence to: tariq.du14@gmail.com

† These authors have contributed equally.

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Chapter 18

Evolution of the Soil-Based Agriculture and Food System to Biologically-Based Indoor Systems

Norman R. Scott

Abstract

There is no area of human activity more basic to society than a sustainable agricultural, food and natural resource system. The 'major' question is, how will food be produced sustainably for the expected global population growth to 9.5–10 billion people by 2050? The agriculture and food system is a highly complex adaptive system, operating across the spectrum of economics, biophysics and sociopolitics. There is a need to move beyond contentious debates between many constituencies, rooted in ideological solutions, to acceptance of a broad array of different approaches. This chapter focuses on the evolution from long and traditionally soil-based systems to biologically-based indoor systems, largely independent of soil with unique characteristics. Science and technology advancements have been critical to achievements of the existing land/soil-based systems and are equally critical in development of the emerging biologically-based indoor systems of controlled environment agriculture (greenhouses and vertical farms) and plant-based food alternatives, cell-cultured foods and 3D printed foods. Thus, there is no system more in need of and more likely to benefit from a comprehensive application of convergence thinking across disciplines and stakeholders.

Keywords: Agriculture, Food, Sustainability, Systems, Digital Ag, Computing and information science, Renewable energy, Sensors, Robots, Drones, Regenerative agriculture, Circularity, Nanotechnology, Biotechnology, Plant-based food alternatives, Cell-cultured foods, 3D printed foods

1. Introduction

With the projections that global population will grow to as much as 10 billion by 2050, there has developed an increasing concern in how this population will be fed, how will food be produced and can it be done sustainably, what will constitute a healthy diet, will the environment be destroyed in the process, will natural resources and ecosystems be compromised, will the food system reduce or increase hunger and poverty, and will the system enhance or decrease equity and access to food for a healthy and productive global population? These and many more critical questions challenge all of us who are a participant in the food and agriculture system (FAS) and every one of us is involved at some level ranging from our daily consumption to innovative scientific research. Thus, one might first ask, what is meant by a food and agriculture system? A report of the National Academy of

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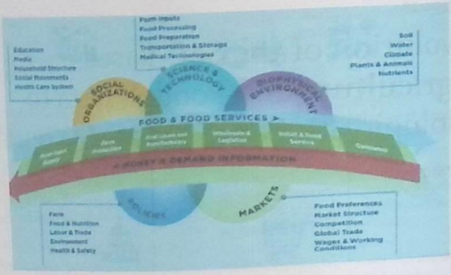

Figure 1.
Links between the food supply chain and the larger biophysical and social/institutional context [1].

Sciences, Engineering and Medicine (NASEM), characterizes the food system as a complex adaptive system that operates across a broad spectrum of economics, biophysical, and sociopolitical contexts [1]. This is captured in **Figure 1**.

The area of Food and Agriculture System (FAS) has been addressed by a number of excellent reports addressing the system from numerous perspectives. Specifically, the World Resources Foundation Report, *Creating a Sustainable Food Future* [2] presents a menu of solutions to feed nearly 10 Billion people by 2050. The report explores 22 items in broad terms that are suggested to stabilize the climate, promote economic development and reduce poverty. An Expert Panel presents a comprehensive report, *Socio-Technical Innovation Bundles for Agri-Food Systems Transformation* [3]. The Panel presents a vision within four core objectives: healthy and nutritious diets (H), equitable and inclusive value chains (E), resilience to shocks and stressors (R) and climate and environmental sustainability (S) which they characterize as HERS.

A report from EAT-Lancet Commission, *Food Planet Health: Healthy Diets from Sustainable Food Systems* [4] emphasizes a goal of transformation from current diets to healthy diets, sustainable food production and reductions in food loss and waste. Walker and Buhler [5] emphasize the role of biotechnology in catalyzing holistic agriculture innovation across a biological scale with a focus on smart machines, advanced sensors, big data, digital science, artificial intelligence, and controlled environment agriculture. A workshop sponsored by the National Academy of Science, Engineering and Medicine (NASEM) explored the future of food in a review of current and emerging knowledge about innovations for food systems [6].

2. "Toward" a sustainable food and agriculture system

Agricultural productivity has been a consistent and important focus during the 20th century and the 21st century, with good reason, to feed a growing world population. However, while providing safe and affordable food remains a driving force for the FAS, there are emerging and numerous factors that challenge our present and future FAS. Some of these are: impacts of the FAS on the environment; trust in science and technology; increasing urbanization; climate change; changing food preferences; globalization; integrated value chains; international regulations;

economic viability of rural communities; and more recently a recognition of the disruption that major events such as a pandemic can create for the FAS. Friedman [7] captures these as a time when the three largest forces on the planet (technology, globalization and climate change) are all accelerating at once, creating the greatest inflection point in history.

Since the 1990's to present, the sustainability of the FAS has become an accepted concept to capture the intersection of environment, economics and equity (or social responsibility). The concept of sustainability arising from the report, *Our Common Future,* [8] has become widely applied to many systems. In the opinion of many people, it has become over utilized and as such does not have significant meaning. Relative to the FAS, the NRC report [9], *Toward Sustainable Agricultural Systems in the 21st Century,* states, "The transformative approach to improving agricultural sustainability.... would facilitate the adoption of production approaches that capitalize on synergies, efficiencies, resilience characteristics associated with complex natural systems and their linked social, economic, and biophysical systems".

The preference of this author is to describe sustainable development as a "process of change in which the direction of investment, the orientation of technology, the allocation of resources, the development and functioning of institutions, and the advancement of human and community well-being meets present needs and aspirations without compromising the ability of future generations to meet their own needs and aspirations" (adapted and modified from [8, 10]). It suggests an imperative for action by which goals for development of the FAS can be measured. Moreover, in addition to implications for resources, it embodies attributes of the environment, economic and social responsibility now and into the future.

At an international level, the United Nation's Sustainability Development Goals [11] have been used widely to encourage development that meets sustainability objectives (**Figure 2**). At first glance it would appear that SDG 2 (zero hunger) would be the primary SDG for the FAS. But on further reflection, it is clear that because the FAS consists of a web of interactions across many complex interlinkages, todays FAS is strongly connected to the other 16 SDGs as well [3]. All of the elements of growing, harvesting, storing, processing, distributing, consuming and managing food losses and wastes are encompassed by the SDGs.

Figure 2.
The 17 sustainable development goals [11].

The recent report, 21st Century Agriculture Renaissance: Solutions from the Land, [12] offers a vision for strategies encompassing climate smart agriculture through 1) sustainable intensification of production, 2) adaptive management and 3) greenhouse gas reduction. The report highlights projects from across the globe and across various farming systems with a focus on indicating which of the SDGs goals are addressed by these respective projects.

3. An evolving food and agriculture system (FAS) to 2050

Domestication of plants and animals can be traced as far back as around 11,000–9,000 BC [13]. From its origin, a fundamental element of the FAS has been a land-based (soil-based) agricultural production system. Today we have experienced the evolution of a highly advanced FAS through emergence of the science and technology of DigitalAg, artificial intelligence, sensors everywhere, internet of things (IoT), genomics (including CRISPR), drones and robots with the one consistent factor being the use of land, the soil. However, 'new' emerging subsystems are developing, based largely on nonland-based, even soilless-based indoor facilities. It is the purpose of this chapter to briefly trace this evolution of the FAS.

First, impressive highlights of key science and technological innovations in the 'conventional' FAS are discussed. Then, science and technological innovations in an 'alternative', largely soilless and indoor system are highlighted. The author recognizes that to do this in one chapter is beyond an ability to cover many significant science and technology innovations, particularly in the 'conventional' FAS. However, the choice has been to focus on science and technologies that are perceived to have potentially a large impact going forward to 2050, and are, in a sense, 'guesses' about a future FAS. A further caveat is there is an over emphasis on the natural sciences with a largely inadequate effort to address the very important social and cognitive sciences.

3.1 Innovations in 'conventional' FAS

The use of 'conventional' is intended to represent soil-based systems. For the purposes of this chapter, science and technological innovations are focused on: (i) computing and information science (Digital Ag), (ii) nanotechnology, (iii) biotechnology, (iv) renewable energy, (v) electrification, (vi) regenerative agriculture, and (vii) circular economy.

3.1.1 Computing and information science (Digital Ag)

The FAS has increasingly embraced computer and information science at many levels from large farmers to poorest farmers in developing countries through an integration of sensors, satellites, tablets and cell phones. Research, teaching and extension (outreach) programs in Digital Ag have been developed in many land grant universities in the U.S. and universities around the world. Like sustainability, Digital Ag is defined or described somewhat differently by various proponents. A description of Digital Ag by the Cornell Institute for Digital Agriculture (CIDA) is given in Figure 3, including linkages to basic elements of innovation, discovery, and analytics with broad applications to areas within the FAS. A key element of CIDA is its ability to bring diverse people together from the Colleges of Agriculture and Life Science, Engineering, Business, Veterinary Medicine, and Computer and Information Science at Cornell University.

Figure 3.
The Cornell Institute for Digital Agriculture.

The capability of Digital Ag ultimately depends on an integration of critical elements for a successful system:

- Sensors (including drones, robotics, artificial intelligence) to initiate data acquisition in the field,
- Autonomous transfer of data from sensors [likely many, an Internet of Things agriculture (IoTA)] by wireless communication with digital devices (computers, tablets, and smart phones),
- Analytical devices with software capability (machine learning, artificial intelligence and handling of 'big' data) for storage, analysis, synthesis and reporting results, and
- Organizations (startups, consolidations and market developments) to apply recommendations to practice in the field.

Given that digitization is spreading through all aspects of food and agriculture one might ask, what is the difference between precision agriculture, smart agriculture and digital agriculture? There is not a unanimous definition, but for purposes of this chapter, the general descriptions offered by [14] are adapted to suggest that precision agriculture seeks to optimize conditions by means of sensory analysis and precise application technology, smart agriculture is a further development of precision agriculture to support decision making, and digital agriculture integrates concepts of both precision and smart agriculture to create value from data.

3.1.1.1 Sensors

It all begins with sensors and with the great advancements in sensor development, it is possible to study plant and animal physiology beyond the laboratory to measure, monitor and activate actions in plant, animal, and microbial production systems. The addition of the Internet of Things, Agricultural (IoTA), big data analysis and artificial intelligence is promoting a high-tech agriculture driven by data. Especially in the application of nanoscale science and technology, sensors and biosensors have been a major area of research and development. In a following section on nanotechnology, numerous examples of sensors in various applications are addressed.

3.1.1.2 Robotics

Robots have clearly moved from many industrial applications to become a significant new technology in the FAS. In labor-intensive crops and in specific identity applications, robots have assumed an important role. A few examples are: (i) identify weeds and implement weed control (e.g., mechanically remove weeds, employ microwave technology to kill weeds, and other methods); (ii) spot onset of plant diseases or pests and deliver intervention schemes (e.g., citrus greening, early potato blight, and many more); (iii) deliver fertilizer, pesticides, and herbicides at specific sites; (iv) spot controlled spray delivery in vineyards and orchards (including pollinator applications); (v) robotic 'duck' in rice fields to control weeds without pesticides; (vi) robots to pick fruit (e.g., apples, citrus, strawberries, raspberries, and more), **Figure 4** illustrates an autonomous fruit picking robot in a development stage; (vii) robot for transplanting; (viii) soil robots for soil testing and determine water-use effectiveness; (ix) in-food processing plants, robots to size, sort and package produce; and (x) autonomous robotic vehicles (including tractors, some electric) to perform field operations that could reduce soil compaction and simultaneously track data.

Robots have entered the dairy farm to milk and feed cows. Cows enter a special stall and are milked while feed is available, during milking based on production. Access to the milking stall is based on n times milking per day as a function of milk production. Cow identity is transmitted by an electronic animal tag and sensors within the teat cup provide data on temperature, milk conductivity, and milk quality. A highly desirable future biosensor would detect progesterone levels that could provide key data on reproductive status (estrus). A single robot station can handle about 40–50 cows per day which makes the system compatible with small farms as well as large farms. The milking robot has been adopted on small farms to address challenges of available human labor, freedom from the commitment of twice daily milking (minimum) permitting a more normal life, and because the cow can be milked more often, increased production has been experienced. **Figure 5** illustrates 2-robots on a small New York dairy with 100 cows. Also, a few large rotating milking parlors with robotic milking units have been installed across the world.

Figure 4.
Flying autonomous robot in development for picking fruit, (https://www.tevel-tech.com).

Figure 5.
Two robots on a New York farm of 100 cows.

The development and production of field and harvest robots is a global business. *Future Farming* [15] has produced a robot catalog with 35 field and harvest robots from sixteen countries. In this first edition, seven of the robots are manufactured in the U.S. and six from the Netherlands. It is anticipated that numbers will continue to increase significantly going forward.

3.1.1.3 Drones (unmanned aerial vehicles, UAV)

While drones (unmanned aerial vehicles) have been widely employed in military missions and for intelligence gathering, their use in agriculture is exploding. Relatively inexpensive and reasonably simple to operate, drones can be equipped with sensors, cameras and specialized hardware to perform a large array of functions in agriculture. Equipped with appropriate devices, drones are: (i) used to develop high-definition maps of fields that provide an ability to create prescriptive-defined application of sprays, fertilizer, pesticides, and herbicides, **Figure 6**; (ii) used to count the number of plants, fruit and flowers to forecast yields; (iii) employed to distribute seeds for crop planting; (iv) used when equipped with multispectral, hyperspectral and thermal cameras to measure chlorophyll, crop biomass, and plant health, as well as determine ground temperature, plant numbers,

Figure 6.
Group of drones capable of performing functions of high-definition maps of fields to create prescriptive-defined application of sprays, fertilizer, pesticides, herbicides and seeding.

soil water content, and estimate crop yields; (v) a potential way to deliver contraceptives to manage wild horse and burro population; (vi) used to monitor a plant's water stress and control irrigation for efficient water use; (vii) used, in absence, or in case of an inadequate number of normal bee pollinators, 'nanobees' (miniature drones) to supplement the pollination process; (viii) use drones in outdoor livestock systems to monitor animals for estrus behavior as well as control and manage the herd, and (xi) employed to monitor and track animals in inaccessible areas in the natural environment.

3.1.2 Nanotechnology

Nanoscale science and engineering offers the potential to significantly revolutionize the FAS. It can play an important role at each point along the FAS supply chain from production through consumption and including management of food losses and wastes [16, 17]. In broad terms, nanotechnology can be a key element in: (i) "re-engineering" of crops, animals, microbes and other living systems at the genetic and cellular level; (ii) development of efficient, "smart" and self-replicating production technologies and inputs; (iii) development of tools and systems for identification, tracking and monitoring; and (iv) manufacture of new materials and modify crops, animals and food products.

The major advancement of applications of nanotechnology in the FAS has occurred largely since 2000. A national research grants program at the USDA/NIFA (United States Department of Agriculture/National Institute of Food and Agriculture) initiated in 2002 has been an important driver of the research in the FAS over the past two decades. The areas of applications have included food quality and safety, animal health monitoring and management, plant systems, environmental systems, and assessment of societal impacts. Just a few applications are: (i) nanomaterials for crop and animal disease detection and detection of residues, trace chemicals, viruses, antibiotics and pathogens; (ii) enhance plant nutrient uptake, nutrient use efficiency, and fertilizer efficiency by controlled release of agrochemicals; (iii) seed coatings with nano-based chemicals to promote seed gemination and deliver long-term disease and pathogen resistance; (iv) DNA-based genetic materials using DNA-based nanobarcodes with a multi-probe sensor to detect pathogens (in plants, animals and environmental contaminants); (v) enhance water-use efficiency in crops by improving water retention and develop 'smart plants' to provide information to meet water needs and manage irrigation; and (vi) wide-spread advances in food packaging and food-contact materials for quality and increased shelf life (eliminate/reduce refrigeration).

Against this significant list of successful developments, the vision for the future of nanotechnology is impressive [17–21]: (i) enhanced sensitivity, selectivity, robustness, ease of use, cost-effective and longevity of nanosensors as key components of the field-distributed, intelligent sensor network for monitoring and control as part of the Internet of Agricultural Things (IoTA), **Figure 7**; (ii) use of common field crops (e.g., corn, soybean, and grains) and trees to make sustainable chemicals; (iii) design nitrogen-producing microbiome and seed coatings that promote crops to produce their own nitrogen fertilizer; (iv) tracking system for integrity of food (plant and animal) from production, transport, and storage to consumer consumption; (v) unique sensors: ingestible to monitor gut health, tooth sensor to measure food properties and chopsticks to detect food characteristics including nutrients; (vi) DNA life-like materials from agricultural biomass ranging from biosensors to biomanufacturing (replace petrochemicals) to development of value-added products including plastics that are biodegradable.

Figure 7.
Graphene sensors on plant leaf to sense water transpiration and measure plant water to control irrigation.

3.1.3 Biotechnology

The impacts of crop biotechnology has been studied over a 22-year period (1996–2018) on farm income and production [22] and on the environment [23]. Significant economic benefits at the farm level globally are estimated at $18.9 billion in 2018 and $225.1 billion (in nominal terms) for the 22-year-period. These gains are attributed at 52% to farmers in developing counties and 48% in developed countries with 72% of the gains based on yield and production increases and 28% from cost savings [22]. Returns on the investment in GM (genetically modified) crop seeds were calculated as an average of $4.41 per dollar invested in developing countries and an average of $3.24 per dollar invested in developed countries.

Assessments of environmental impact on GM crops estimate reduced global crop protection products use by 8.6% over the 22 years. Reduced GHG emissions through adoption of reduced tillage, that reduces fuel usage and improves soil carbon retention, are estimated to have an environmental impact reduction of 19% [23].

The annual report of the International Service for the Acquisition of Agri-biotech Applications (ISAAA) provides a yearly global update on adoption and distribution of biotech crops [24]. The 2019 report shows that GM crops increased to 29 countries with 190.4 billion hectares. A total of 72 countries have adopted biotech crops with 29 having planted crops and 43 additional countries importing biotech crops for food, feed, and processing.

The biological world in 2020 was marked by recognition of CRISPR (clustered regularly interspersed short palindromic repeats) with a Nobel Prize in Chemistry awarded to its inventors. Simply stated, CRISPR is a unique technology used to edit select genes by finding a specific bit of DNA inside a cell and then altering that piece of DNA. Already applied in human health, it is being used in plant science for traits that can prevent disease, create pest resistance, increase resiliency, and improve crop yields.

Animal biotechnology has contributed greatly to increasing livestock productivity through increased production, reproductive efficiency, genetic improvement, animal nutrition, and animal health [25]. Specifically recombinant bovine somatotropin (rBST) has been shown to increase feed conversion and milk yield. Major advances in animal reproduction has been experienced with biotechnology applied to genetics and breeding. The U.S. Food and Drug Administration approved in December 2020, a first-of-its-kind, intentional genomic alteration (IGA) in domestic pigs for food or human therapeutics [26].

Thus, if we are to create new crop varieties and increased yields and improved animal breeds, it is important to utilize the science of biotechnologies to advance benefits for both large and small farmers. The impressive potential of biotechnology should not be ignored and left underutilized.

3.1.4 Renewable energy

3.1.4.1 Solar energy

The challenges of meeting the needs of food, energy and water (frequently called a nexus) in the face of climate change have stimulated some innovative novel systems to co-locate agriculture and solar photovoltaics (PV), termed 'agrivoltaics'. The concept originally suggested in 1982 [27] has been further developed and analyzed by [28–31]. At present solar PV is being employed by large utility-grid systems and on rooftops but the opportunity to develop an integrated system with coupled application of PV and crop production on the same land maximizes land use without sacrificing crop land. In fact, a study of collocation in drylands [31] has shown synergistic benefits of reduced plant stress, improved yields and reduced PV panel heat stress. Development of enhanced semi-transparent PV panels would further advance collocation of PV panels and crop land. A conceptual rendering of the concept is illustrated in **Figure 8**.

Although **Figure 8** illustrates the solar PV panel elevated ('on stilts') to allow animals and equipment to move beneath the panels, another option could be ground mounted PV panels separated by an area between panels for farming [28]. At this point, the number of crops which have been evaluated under PV panels is limited. Also, the impact of PV panels on the microclimate of air temperature, wind speed and relative humidity needs significant study to assess plant response. Some studies have shown benefits for crops like tomatoes, and lettuce [30].

Figure 8.
A conceptual presentation of collocated solar PV and agricultural land with crops and animal production.

3.1.4.2 Wind energy

Much has changed from the early 1900's when many farmers used wind power to pump water and generate power from relatively small windmills. Today large wind turbines with generating capacity well above 1 MW are common on agricultural land, particularly in the West and Midwest, although many wind farms are found in other areas as well [32]. Like for solar PV, collocation of wind turbines on agricultural land has become common place. Farmers can lease land to wind developers, own turbines to generate power for their farm or as a farmer or group of farmers become a wind developer. Many farmers have found wind turbines on their land to be an important source of income. Typically, large turbines use a half-acre or less, including the access road, while allowing farming operations for cropping and grazing of livestock up to the base of turbines, **Figure 9**. As one farmer has been known to say, "it is a lot easier to milk a wind turbine than cows".

3.1.4.3 Bioenergy

3.1.4.3.1 Biofuels

At a time when the U.S. was dependent on imported transportation fuels, a Renewable Fuel Standard (RFS) was enacted by the Congress to create annual mandates for production of conventional biofuels and advanced biofuels. Corn ethanol became the predominant conventional biofuel and cellulosic-derived fuels as advanced biofuels. Significant controversary surrounded corn ethanol because of concerns of effects on food/feed prices, distortion of land use, increased cropland prices, and uncertainties about claims of environmental benefits. A report of the National Research Council (NRC, [33]) presented two findings: (1) the RFS may be an ineffective policy to reduce GHG emissions because the amount depends on how biofuels are produced, including changes to effects on land use, and (2) barriers to achieving the RFS due to high costs in producing cellulosic biofuels and market uncertainties. The U.S. Energy Information Administration [34], in projections to 2050, projects that the % of biofuels (ethanol, biodiesel and other biomass) may increase a bit between 10 and 13% depending on the scenario for oil prices.

Figure 9.
Large wind turbines integrated into agricultural crop land.

3.1.4.3.2 Biogas

A process using microorganisms, specifically a suite of bacteria, have been utilized to convert organic materials into biogas, primarily methane (~60–70%) and carbon dioxide (~30–40%), with small quantities of trace gases. Anaerobic digestion using methanogenic bacteria, in the absence of oxygen in airtight structures, has been used for many years, ranging from small home-owned digesters in China to advanced systems with increasingly large commercial tanks, highly instrumented in the U.S. and Europe. These large systems have been developed to manage animal manures together with food and other organic wastes by co-digestion to provide energy options of combined heat and power (CHP) and pipeline and transportation fuels) following processing and compression [35].

Anaerobic digesters number more than 250 in the U.S. while the number in Germany is now about 9,000. Germany has been particularly adept at using biogas to power bioenergy villages illustrating the potential for distributed energy generation in rural communities. It has become clear for economic success of anaerobic digesters that they operate as co-digesters by adding other organics in addition to animal manures [36]. Beyond direct products of biogas and digestate options, anaerobic digestion offers manure management opportunities for environmental benefits of reduced odors, reduced pollution and reduced GHG emissions. Opportunities for collaboration between businesses and farm digesters exist and are increasing. A recent example of this collaboration is a venture with founding members, Unilever, Starbucks and Dairy Farmers of America.

3.1.5 Electrification on the farm

The Rural Electrification Act of 1936 revolutionized rural America. Electric vehicles are revolutionizing the transportation sector. This revolution is also taking place in agriculture at an early stage with numerous equipment manufacturers launching, or working to develop, autonomous electric tractors [37]. Tractor companies, Monarch, Solectrac, Kubota, AGCO and John Deere to mention a few, are investing heavily in electric tractors and are in various stages in their development with the potential of limited availability as early as 2021. These tractors are equipped with autonomous hardware replete with many sensors and machine learning for data collection and tractor control.

At this point development of the electric tractor has been focused in the 30–40 hp. (horsepower) range (25 – 30 kW), largely due to the size and weight of batteries. An advantage of smaller equipment is potential for reduced soil compaction. **Figure 10** illustrates two experimental paths of John Deere, a battery-driven tractor and an electrically connected tractor (a long extension cord!).

First perceptions are that this high technology would be only applicable and affordable in 'industrialized' agriculture. However, the possibility of developing

Figure 10.
John Deere's battery-electric tractor and connected electric tractor.

electric-driven tractors and equipment is certainly conceivable in the developing world because smaller tractors and machines are well adapted to the small land holdings. The author envisions the co-development of solar PV for charging batteries to power electric equipment. Rapidly developing advancements in battery technologies and decreasing cost will be keys to adoption in the developing world. The unique idea of a cord-connected electric tractor, while not likely to be an option in U.S. agriculture, might well be an excellent way to connect solar PV to power electric equipment for the small farmer.

3.1.6 *Regenerative agriculture*

As previously noted, agriculture is coming under increasing scrutiny because of GHG emissions and negative effects on the environment. Drawing much attention recently is the practice referred to as 'regenerative agriculture". The term has no universal definition but is frequently used to describe practices to promote soil health by increasing soil organic carbon [38]. Practices commonly perceived to advance regenerative agriculture are no-till farming, cover crops, diverse crop rotations, rotating livestock grazing, and lessened use of fertilizers, pesticides and herbicides. Cropping system diversification has been shown to reduce negative environmental impacts of soil erosion and nutrient runoff, and reduced cropping inputs while maintaining crop yields [39, 40].

While there is general agreement that regenerative agriculture practices improve soil health and provide environmental benefits, some researchers [38] report that regenerative agriculture practices have limited potential to increase soil carbon sequestration. Nevertheless, some corporations have set up a carbon sequestration market (Bayer) and a carbon credit for soil carbon sequestered (Land O'Lakes) for farmers. In addition, Cargill, McDonald's, and Walmart Foundation are collaborating with the World Wildlife Foundation on regenerative practices to improve grasslands of the Northern Great Plains.

It is suggested that going forward farmers will be paid for soil carbon storage. However, this requires an ability to measure soil carbon and quantify change in the field accurately over time to assess the effects of differing practices. Thus, future research is needed to find new ways of soil carbon sequestration and develop the data through measurement of soil carbon content.

3.1.7 *Circular economy in FAS*

The concept of has been recently introduced in the FAS. The guiding principle is to: (1) design out waste and pollution, (2) keep products and materials in use and (3) regenerate natural systems within the FAS [41]. The Ellen Macarthur Foundation [41] articulates three ambitions for a healthy urban food system as: (1) source food regeneratively, and locally where appropriate, (2) design and market healthier food products, and (3) make the most of food. For too long the FAS has been primarily a linear system from production, postharvest, processing, distribution and consumption without regard to wastes incurred along the value chain.

Although recently introduced in the FAS [42], the fundamental concept has been applied and described by terms like 'industrial ecology' or 'industrial symbiosis' in numerous areas. It has been employed to mean that a waste from an entity (business, for example) would become an input to another entity (business), thereby circulating materials and keeping them in use within the larger system, essentially the concept of an 'ecosystem' [43]. This concept has not been adopted widely, although the concept of a 'Food Eco-Industrial Park' would be intriguing.

Specifically, technologies and systems applied along the value chain are needed to reduce food losses and wastes which are estimated to be as much as 30–50% globally and remarkedly similar across regions.

3.2 Innovations in controlled environment food and agricultural systems (CEFAS)

Emerging technological innovations, particularly over the past two decades have developed, based largely on a nonland-based or soilless-based indoor systems. These developing initiatives are captured by the term, 'controlled environment food and agricultural systems" (CEFAS) broadly, and more specifically by emerging subsystems, 'controlled biologically-based indoor food systems' (CBIFS).

CEFAS has evolved from a protected environment provided by greenhouses, originally with soil as the growth medium to advanced greenhouses with nutrient solutions to replace soil. Vertical farms have evolved further by using height (vertical) dimension to create intensification of the growing environment and greater yields per m^2 (production area). Both advanced greenhouses and vertical farms employ highly sophisticated measurements, controls and management. Sensors, computer control, artificial intelligence, machine learning and robots are common. These technologies are primarily devoted to growing fruits and vegetables and not practical for common field crops such as corn, soybeans, cereal grains and tuber crops, although recent research has studied the potential for wheat grown in vertical farms [44]. In addition, an increasingly significant area of a sustainable food future is aquaculture and specifically the development of the recirculating indoor system.

3.2.1 *Recirculating aquaculture systems (RAS)*

Fish, including finfish and shellfish, contribute about 17% of global animal-based protein for human consumption and particularly so in developing countries which consume more that 75% while producing greater than 80% of the global fish supply [45]. A major concern is that the annual number of fish caught in the wild, particularly in the oceans, has stagnated since the 1990s. As world consumption of fish has grown, aquaculture (fish farming) has developed, and almost half of the fish consumed comes from aquaculture. It is estimated that aquaculture production needs to double from approximately 67 million tons (MT) in (2012) to about 140 MT in 2050 [2].

Aquaculture, as described above, is based primarily on confined operations in a water environment, marine, such as 'cages' in oceans (along coasts predominately) or freshwater, outdoor ponds on land. The concept of a recirculating indoor aquaculture system (RAS) over the past several decades has emerged as an alternative system with advantages of greatly reduced land use and major reduction in water requirements compared to ponds. Simply stated the water is filtered from the growing tanks (confined environment) and recycled for reuse in the tanks, **Figure 11**. RAS have performed well relative to measures of productivity and environment parameters. A comprehensive treatment of recirculating aquaculture systems is provided by [46]. Challenges persist because of high capital costs, feed sources, concern for fish diseases, food safety, and consumer acceptance. Consumer concerns that farmed fish tend to have lower levels of omega-3 fatty acids than wild fish [47] and concerns about the highly intensive growing environment have limited acceptance.

Aquaponics can be an added element to an RAS by combining plants and fish. In an aquaponics system, fish provide waste that effectively fertilizes plants, thereby

Figure 11.
A recirculating aquaculture system.

creating a closed loop system (circular economy) [46]. Plants act essentially as a filter by taking up nitrates in the system. The benefits are little waste from the overall system and inputs are minimized.

Clearly, as noted, large projected increasing consumer interest for seafoods provide a need to advance aquaculture generally and RAS specifically. Thus, efforts to intensify aquaculture production by RAS need to be directed at approaches to mitigate negative issues of RAS.

3.2.2 Greenhouses

The concept of growing plants in environmentally controlled areas can be traced back to Roman times [48]. The concept of the greenhouse, as we have come to know it today, began in the Netherlands and then England in the 17th century. They have evolved from simple row covers to very large structures in the 1960s when materials such as polyethylene films, aluminum extrusions, special galvanized steel, and PVC tubing became available for various structural support frames.

3.2.2.1 Basic greenhouses

For purposes of this chapter the basic greenhouse is one where a plastic film (polyethylene) is supported by a light frame, often a hoop or A-frame in form. This type of greenhouse is primarily dependent on solar energy for heat in a cold environment, although some heating device may be employed in severe situations. Any ventilation is accomplished by natural ventilation with manual openings or slots to promote air flow for cooling. In times of high solar energy, shade coverings such as clothes are used. The plants are grown in soil at ground level or in raised beds. Movement of plants and materials are managed manually by humans with assistance of simple devices and equipment. Because the costs for the basic greenhouse are relatively low, they are used in small farm operations or in many urban settings.

3.2.2.2 Advanced greenhouses

The advanced greenhouse is defined here as a greenhouse with a highly controlled environment, high automation under computer control and using a soilless growing medium, hydroponic solution. The controlled environment for plant production consists of intensive assessment of the environment by numerous sensors to measure and monitor the parameters of: temperature, pH, relative humidity, dissolved O_2 in nutrient solution, electrical conductivity for dissolved salts in nutrient solution, CO_2 of inside air, and light intensity from the sun and supplemental lighting, and PAR (photosynthetically activated radiation) in μmol/m^2/s. Quality and optimum plant growth is dependent on plants getting an optimum daily quantity of PAR (mol/m^2/d). If the daily PAR is not provided by the sun, the computer will implement supplemental lighting to meet the desired value, **Figure 12**.

An advanced greenhouse consists of a complete system from germination of seeds to the finished product. Typically, the seed is planted in a fibrous material such as rockwool cube to germinate. Following germination, the cubes are inserted into a material (like Styrofoam) to float on the surface of the nutrient solution until fully mature.

Temperature will be controlled typically by mechanical fan ventilation under computer control of air flow by managing air intake openings. Where appropriate evaporative cooling may be used to provide cooling. Addition of CO_2 can be added to increase plant growth. Shading material can be used to reduce excessive solar energy and moveable insulation can be used to reduce heat loss at night respectively. Beyond the controlled thermal and growing environment, the advance greenhouse will include a significant automation for materials handling including robots [49].

3.2.2.3 *Vertical farms (VFs)*

Based on advances discussed for advanced greenhouses, the vertical farm uses the vertical dimension (**Figure 13**) to grow plants in stacked layers thereby increasing greatly the amount of product grown per unit area [50–53]. Like for the advanced greenhouse, the growing environment in a vertical farm is closely controlled for temperature, humidity, ventilation and the properties of the nutrient solution, including introduction of robotics. Five reasons to take vertical farms seriously are: avoid effect of weather and weather extremes, large reduction in water usage by as much as 95%, plant yields are high and the growing cycle is short, lower food losses, shorter supply chains because VFs can be located in urban areas, and products can be produced year-round [54].

Key challenges for VFs are high capital and energy costs. The issues of high energy consumption in VFs is due to full artificial lighting (LEDs) and for meeting cooling and humidification loads. More efficient LEDS and using LEDS tailored to the light spectrum for the specific crop, rather than the full spectrum, may save

Figure 12.
An advanced controlled environment greenhouse.

Figure 13.
A vertical farm.

electricity. Possibly the residual heat could be used in a surrounding case where a need for heat is needed. Clearly, because of large capital costs and energy requirements VFs will be a 'niche' system until these are resolved. In comparison with advanced greenhouses, where solar energy is utilized and where greenhouses can also be located in urban environments (rooftops and vacant lots for example), VFs would seem to offer uncertain benefits.

Efforts to conduct a Life Cycle Assessment of VFs and, in addition, approaches for an integration of VFs into cities are critical to assess the future of VFs. Numerous VFs have been developed and a substantial number, as well, are in the planning stages in the U.S. and Asia. Some of these are conceptualized to include solar energy directly, and inclusion of aquaculture and even livestock production [55].

3.3 Innovations in 'alternative', biologically-based indoor food systems (CBIFS)

Foods, like all materials, are an assemblage of molecules arranged in a specific structure and one is witnessing significant new biological/biochemistry efforts to create foods from plant or animal cells from the 'bottom up'. Three technologies (CBIFS) are characterized in this overview as: (1) plant-based alternative foods, (2) cell-cultured foods, and 3D printed foods. Because they use biochemical building blocks from proteins, carbohydrates, fats, and oils from plants and animals, CBIFS is a 'new' agriculture.

While much of the hype has been directed to burgers [56], there has been substantial advancement of other alternative foods, such as, for eggs, fish, shrimp, milk, yogurt, chicken nuggets, and chicken tenders to mention a few. The objective of CBIFS is to develop food products that mimic traditional foods with significant benefits. The benefits can be: (i) an environment unaffected by weather/extreme weather; (ii) year-round production; (iii) shortened growing cycles and higher yields; (iv) reduction in land, energy, and water use, (v) lower food loss and waste; (vi) shorter supply chains, local access compatible with urban settings; (vii) reduction or elimination of pesticides and antibiotics; (viii) reduction of GHG emissions; (ix) reduction in water pollution; (x) potential for enhanced micronutrients, and (xi) eliminate animal welfare concerns (growing conditions and slaughter).

However, there are potential uncertainties (questions), such as: (i) high capital cost; (ii) timeline to market; (iii) in some cases, high energy consumption; (iv) consumer acceptance; (v) concern about food quality and safety, particularly nutritional content and presence of growth hormones; (vi) price to consumers,

(vii) potential contamination; (viii) impact and possible detrimental effect for small farmers; (ix) proprietary nature of processes; (x) unproven technology, and (xi) whether the CBIFS benefits large-scale economies to the detriment of markets for small farmers [56–58].

Sustainability is critical to any future food system and is a driving force for CIBFS. In broad terms, CIBFS seeks to develop foods that impose less environmental impact, enhance human health, and reduce ethical implications of traditional animal-agriculture production, particularly for meat. Global meat consumption is estimated to increase 3% per year to 2040 [59, 60]. However, several groups [60, 61] forecast a major protein disruption in the conventional animal-agriculture system where engineered foods at the molecular level will lead to a reduction of as much as 50% or more from conventional meat and dairy by 2040.

In this section, a brief overview is presented for three types of CIBFS: plant-based alternative foods, cell-cultured foods and 3D printed foods. Through research and development each of these subsystems has a potential to enhance sustainability, availability, reliability, consumer acceptance, and quality and safety of food production.

It should be noted that food cost to the consumer is a critical issue for success of any new product. Over the past 5–10 years, numerous entrepreneurs, start-ups and food companies have created alternative foods that are already in the marketplace. In many cases, the price to consumers, at present, is higher than equivalent traditional foods, but the difference has decreased over time. As these emerging alternative products are improved, it is likely that cost to the consumer will be reduced to be comparable or even less. The food system is a high complex, adaptive system and like in other emerging technologies, there will be major changes with business failures and new players going forward.

3.3.1 Plant-based alternative foods

The development of plant-based alternative foods has become a very hot area, particularly for plant-based meat alternatives [58, 62–64]. Development of plant-based meat alternatives have attracted the greatest public attention. Environmental, human health, and concerns for animal welfare are prime factors. Among more than 50 manufacturers currently, (*Beyond Meat, Light Life and Impossible Foods*), are leading developers of plant-based burgers that are widely available in grocery stores, restaurants, and online. While burgers are a major food product, other products such as ground beef sausage, bacon and hotdogs are available.

Globally the food and agricultural system is estimated to generate as much as 34% of total GHG emissions with 71% from agriculture and related land use and land use change [65]. The opportunity for plant-based alternatives to substantially reduce environmental impacts was determined in a comparative study (Life Cycle Assessment-LCA) of the *Beyond Burger* and a U.S. beef burger (quarter pounder) by the Center for Sustainable Systems at the University of Michigan [66]. The selected parameters were GHG emissions, cumulative energy use, water use, and land use. The comparison was made to an LCA study by the National Cattleman's Beef Asssociation [67]. For the *Beyond Burger* system the results showed 90% less GHG emissions, with 46% less energy, 99% less water and 93% less land use. *Impossible Foods* also commissioned a study which found that their burger uses 96% less land, 87% less water and 86% less fossil fuel than a quarter pound beef burger. Independent LCA studies would be beneficial, given the rapidly changing ingredients being used to create plant-based meat alternatives.

Plant-based protein sources (legumes and cereal grains) are an important choice for both the vegetarian and traditional meat consumer. However, challenges remain for developers of plant-based proteins to deliver a healthy, nutritionally safe, tasty flavor, texture and appearance (color) comparable to traditional products. Because the development of plant-based meats involves complex processing of many ingredients, there have been concerns expresses about health benefits. One report [68] reviewed formulation and nutrient content of some common commercial products (burgers, hams and chicken nuggets) which contained as many as 20–30 ingredients. Comparisons yield a mixed story because plant-based meats provide about the same calories as traditional meat with more sodium, more potassium (helps eliminate sodium), no cholesterol, more iron, more B vitamins, more calcium and more saturated fat. Also, there have been reported concerns [69] about whether high-temperature cooking (grilling, frying, etc.) of protein foods could generate toxins and carcinogens. Thus, there is a need to assess whether plant-based meat protein would be any less safe or safer than traditional meat.

Consumer acceptance of plant-based meats and food products is key to the ultimate impact of these products. Substantial improvements have been made during the decade with plant-based burgers such that many people find them indistinguishable from a traditional burger. Nevertheless, the author suggests the need for future research and study in: (i) independent LCS studies to quantify environmental benefits; (ii) further evidence on health benefits, nutrition, and safety; (iii) development of new plant proteins sources; (iv) reduction in number of non-protein ingredients; and (v) reduction in cost to consumer.

3.3.2 *Cell-cultured foods*

Cell-cultured meat, also known as cultivated meat, has advanced at a rapid pace over the past 20 years. The concept, although relatively simple, uses animal cells nurtured within a bioreactor to produce food that is designed to mimic meat products [70]. Compared to plant-based protein where protein is extracted from plants, cell-based meat is created from cells extracted from animals and grown in a culture. Specifically, a small piece of fresh muscle, obtained by biopsy, from a living animal is disrupted by a combination of mechanical and enzymatic methods to produce stem cells [71].

Using culturing methods, the adult stem cell (called satellite cells), in the presence of relatively high serum concentrations, divide leading to multiplying populations. Tissue engineering methods are then used to differentiate these expanded cells into muscle and fat tissue, which lead to generation of a cultured meat product closely resembling conventional meat [72]. **Figure 14** illustrates, in broad terms, the process based on the starting point of obtaining adult muscle stem cells from an animals or pluripotent stem cells from an embryo [73]. However, a recent study suggests that it may be possible to grow cultured meat with much less dependence on animals by using a soy-based scaffold for support of muscle cells and form a meat-like 3D-cell structure [74].

Today, there is no cultured meat available for consumers to purchase at retail or food service outlets in the U.S., unlike plant-based meat, but there are 20 or more start-ups in the cultured meat space [60]. However, the Singapore Food Agency approved in December 2020 a cultured chicken product by Eat Just [75]. With an investment more than $100 million in global funding by billionaires and venture capitalists, there are significant efforts to develop the area [55].

It is very difficult to reproduce the diversity of meats from the numerous existing animal species, breeds and cuts so there is a great need to optimize cell culture technology [76]. A LCA [77] and a (TEA) techno-economic assessment [78] have modeled future large-scale cell-cultured meat production facilities and have shown reduced overall environmental impacts and the potential to be cost-competitive

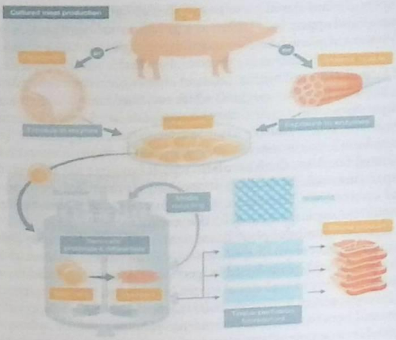

Figure 14.
The development process for cell-cultured meat [73].

with conventional meat by 2030. These are the first repots using data collected from active companies (more than 15) in the chain. The LCA shows cell-cultured meat is about 3.5 times more efficient (feed conversion ratio) than poultry which is the most efficient system of conventional meat production. The LCA in its comparisons with traditional meat includes the use of renewable energy in which case the reduction in GHG emissions shows a reduction of 17–92%, less land use of 63–95% and 51–78% less use of water depending on the respective conventional animal system.

However, studies by [76, 79] suggest that comparison is not that simple. They conclude that the relative comparisons with conventional meat depend on the type of systems for energy generation (i.e., decarbonized and renewable) and the specific production animal system. Thus, there is a need for independent and transparent LCA studies of cultured meat production.

A major challenge for cultured meat production is meeting consumer demands for flavor, texture, color, nutritional composition and cost [80, 81]. Conventional animal meat is high in protein with amino acids, vitamins and minerals. As development of cultured meat has advanced, the similarity to conventional meat has improved greatly, such that many people cannot distinguish a difference between the two [55]. An advantage that cultured meat can have is an ability to add texturizing ingredients, colorants, flavorings and nutrients to address sensorial and nutritional properties [80]. Challenges facing cell-cultured meat systems include: (i) replace animal serum with plant materials; (ii) reduce costs by material substitutions and advances in scalability; (iii) assessment of health effects, short and long term; (iv) conduct detailed, independent and transparent LCAs to quantify environment impacts; (v) eliminate growth hormone factors; (vi) develop cell lines that are more accessible; vii) safety assessment, particularly with respect to potential contaminants that might enter in the process; (viii) ability to replicate the diversity of conventional meats; (ix) address the issues of potential regulation, as well as labeling, and (x) develop a name or nomenclature for marketing (presently there is much variation and uncertainty about a common name).

3.3.3 3D printed foods

The combination of robotics and software has entered the realm of food manufacturing in the form of 3D printing [81–84]. 3D printing technology is a novel approach which can create complex geometries, tailored textures, and nutritional contents. The 3D technology can provide a 'customized food' to meet special dietary needs as well as mass customization. NovaMeat, a Spanish company, and Redefine Meat, an Israeli company, have utilized 3D technology to produce beef steaks and other meats that resemble animal meat.

In the 3D printing process, food ingredients are placed in cartridges, and the product is created layer by layer by a controlled robotic process, similar to 3D printing of non-food items. The technology has been employed to use tissue engineering to create meat and other food alternatives. Also, the 3D technology has been employed at the home scale to create 'designer 'foods. Depending on the specific food, ingredients can range from processed components (sauces, dough, etc.) to more elemental ingredients such as sugars, proteins, fats, and carbohydrates [82]. Some foods may require further processing, such as some form of cooking or storage. A significant challenge is linking material properties and structure to the printing process variables to get a desired 3D printed product. The parameters of control are those relating to the printer and those controlling the food-relevant parameters.

In Switzerland, Jungbunzlauer AG [85] is providing 'recipe cards' to guide consumers to use bio-based ingredients to create one's own dairy and meat alternatives. Recipe cards are available online to create foods such as non-dairy ice cream, cream cheese and yogurt as well as plant-based burgers and bratwurst. The respective recipe card provides a detailed list of ingredients, suppliers, quantities, together with directions to create the specific food product and with nutrition information as well. Thus, it seems not to be a great stretch that this information could lead to 3D printing of designer and specialized food products.

The 3D printing process compresses the value chain to a highly local system of inputs (ingredients), a single controlled process (the 3D printer) and a single output (the food product).

4. Conclusions

Meeting the demand for food of the growing world population will require both conventional land-based agriculture systems and controlled environment agriculture and food systems, including emerging controlled biology-based indoor food systems (CBIFS).

Already during the 21st century the impact of innovations in 'conventional' agriculture and food systems has been impressive:

- Digital Ag, driven by computing and information science, has progressed rapidly to offer technically advanced solutions to support an efficient FAS with decreases in food loss and waste with greater productivity, prosperity, and sustainability, with more to come,
- Sensors, robots and drones are, and will become even more ubiquitous moving forward,
- Nanoscale science and engineering, and biotechnologies (particularly CRISP) will continue to drive innovations in many areas of the FAS,

- Renewable energies of solar, wind and bioenergy are increasingly integrated into the FAS through co-location of sources on the land, as well as providing sustainable energy for rural communities, domestically and internationally,
- Electricity will be an increasing driving force in FAS for motive power of agricultural machines, including tractors and autonomous systems,
- Emphasis on the soil health is likely to increase substantially as a part of the initiatives in regenerative agriculture practices if it proves profitable and successful in sequestering significant carbon, and
- Circularity in the FAS is likely to be a major initiative in an effort to design out waste and pollution, keep materials in play and to maintain natural systems.

In acknowledging the fact that traditional FAS uses substantial land and creates considerable GHG emissions, an emerging area of food production has developed. Controlled Biologically-based Indoor Food Systems (CBIFS) can greatly reduce land area for agriculture production by largely soilless methods and produce foods with less environmental impact, enhance human health and avoid ethical concerns about traditional methods, particularly for meat. CBIFS described herein: recirculating aquaculture, advanced greenhouses, vertical farms, plant-based alternative foods, cell-cultured foods and 3D printing of foods are in various stages of development but are poised to grow in the future. Principal keys to growth are costs to the consumer and consumer acceptance. Nevertheless, numerous products are in the marketplace and already enjoy modest growth.

CBIFS use basic biochemical building blocks of proteins, amino acids, sugars, fats, carbohydrates, and oils from plants and animals. Thus, controlled environment agriculture and food systems, including CBIFS, should be viewed as complementary to conventional agriculture and typical supply chains. Further development of CBIFS foods that are as healthy, nutritious, safe and appealing as conventional foods will significantly contribute to the sustainability, resilience and circularity of food and agriculture systems.

Finally, there is a need to transcend the debate between numerous constituencies, rooted in ideological attitudes, to invoke and encourage an array of different approaches to meet the challenge of a food and agriculture system that is robust, safe, and sustainable in meeting the 17 Sustainable Development Goals for a sustainable planet.

Author details

Norman R. Scott
Department of Biological and Environmental Engineering, Cornell University, Ithaca, New York, USA

*Address all correspondence to: nrs5@cornell.edu

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Section 3

Energy Systems Engineering

Chapter 19

Adsorption-Based Atmospheric Water Harvesting: Technology Fundamentals and Energy-Efficient Adsorbents

Muhammad Sultan, Muhammad Bilal, Takahiko Miyazaki, Uzair Sajjad and Fiaz Ahmad

Abstract

Nowadays, atmospheric water harvesting (AWH) became very essential to provide fresh potable water. This technique is in practice since 1900 (US661944A) by Edger S. Belden. Atmospheric water is a source of freshwater with 13000 trillion liters availability of water at any time and can be utilized in overcoming water shortage, especially in arid and rural areas. It holds up the water molecules in the form of vapors and accounts for adding 10% of all freshwater present on the earth. Mainly, the two most common methods have been used for the extraction of atmospheric water. First, the ambient air is cooled below the dew point temperature, and second in which the moisture in atmospheric air is adsorbed/absorbed using desiccant materials. Conventional vapor compression, thermoelectric cooling, dew, and fog water harvesting based systems/technologies possess some limits in terms of energy requirements, less efficiency, and high cost. However, the adsorption based AWH technology is relatively cheaper, environment friendly, and can be operated by a low-grade thermal energy source. The limited availability of commercial instruments to harvest atmospheric water using adsorbents indicates a lack of fundamental studies. The fundamental research on water adsorption, adsorption kinetics, regeneration conditions, and water collecting surface designs has not gained as much interest as required in the field of atmospheric water harvesting. In this regard, this book chapter discusses and presents the progress in the field of adsorbent materials and system designs along with the future directions to accelerate the commercialization of this technology.

Keywords: adsorption, desiccant dehumidification, atmospheric water harvesting, energy-efficient adsorbents, thermal energy, condensation

1. Introduction

Globally, water scarcity is considered one of the prime issues in the upcoming decades. Almost 2.1 billion people are lacking access to clean and fresh water [1]. **Figure 1** shows the water-stressed areas in the world. Middle East, Asia, South America, and some parts of Africa face water scarcity. Therefore, many studies

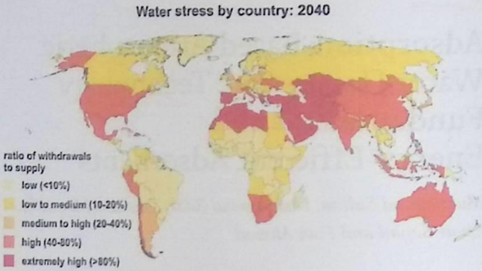

Figure 1.
World map showing the water-stressed areas by 2040 reproduced from [2].

have been investigated to supply enough water with cheaper, and portable methods [3, 4]. These methods include desalination, wastewater treatment, sewage recycling, and water harvesting from the atmosphere. The energy consumption in desalination systems is very high that is almost 50% of the cost, and make this technology inappropriate in most situations [5]. Also, seawater desalination is not suitable for remote areas and has many environmental problems. Thus, portable systems with less energy consumption are needed. Atmospheric water harvesting can be considered as a potential resource of fresh water in remote areas [6]. For this purpose, many researchers have introduced innovations for water production from humid air technology. This can be done by many ways i.e., using vapor compression cycle (VCC) [7–10], thermoelectric cooling (TEC) [11, 12],

Figure 2.
Summary of various technologies for water production from humid air available in the literature [28].

absorption/adsorption refrigeration [13, 14], wind power with VCC [15], using solar chimneys [16, 17], using membranes [18, 19], and using adsorbent materials [20–27]. **Figure 2** summarized the various technologies investigated in the literature for producing water from the humid air. The purpose of all these technologies is to produce water and are using worldwide depending on the conditions and the requirements. Among all these technologies, desiccant based atmospheric water harvesting (AWH) shows a great potential to extract enough amount of drinkable water with less energy consumption [6]. The adsorption based AWH is possible in dry and desert regions with the lowest relative humidity. This technology utilizes renewable energy sources (solar, wind, and low-grade biomass) which ultimately lead towards the cheapest and most efficient systems. This chapter focuses on the fundamentals and principles of adsorption based AWH. The progress and perspectives and associated adsorption based AWH systems are also discussed in this study. Moreover, energy-efficient desiccant materials along with the recently developed new generation MOFs for AWH are also highlighted in this study. The main purpose of this chapter is to introduce the importance of AWH by employing various efficient desiccant materials.

2. Atmospheric water harvesting

2.1 Conventional AWH

Atmospheric water harvesting could be considered as a huge renewable source of water that can provide enough amount of water, but unfortunately is ignored [29]. Conventional water harvesting was started first when a Russian forester built a stone condenser during 1905 and 1912 and was considered as the early Greek dew condenser [30, 31]. Ziebold tested with this type of condenser and named as "the aerial wells", but unfortunately, this project was failed and the expected amount of water was not produced due to the low thermal conductivity and low heat capacity [32]. In 1957, a review was carried out on the absorption of water by the plants [33]. Since then several studies have been carried out focusing on the fog and dew harvesting by the plants and animals [34].

2.2 Modern AWH

Modern AWH shifted towards the innovations, methods, and technologies that can provide a significant amount of water in remote areas [35]. As mentioned earlier in the introduction section, various new methods have been proposed for AWH i.e., VCC, TEC, using membrane and adsorbent materials. Among these, the fog water was first collected with the help of nets in 1956 [36]. Shi et al. replaced these traditional meshes with vertically arranged wires to avoid the problems of clogging [37]. Dew water collection considered as the alternative approach because it is not majorly affected by climatic conditions and can provide water in most of the ambient environment [38]. A lot of advancements have been done in the designs of active condensers after the commercialization of mechanical refrigerators in the 1980s. The desiccant based dew water harvesting was taken into consideration in the Nineteenth century, in which the various desiccant materials capture the moisture from the atmosphere during the night, and then releases the moisture in vapor form during the day. This method has been proved the most energy-efficient and reliable technology because it employs solar energy and can provide water anywhere and anytime in the world.

3. Water vapor parameters in atmospheric air

Atmospheric air is a mixture of nitrogen, oxygen, and argon gas, and water vapors with varying contents. The relative humidity (Φ), absolute humidity (ω), and the dew point temperature (T_d) are considered as the most essential parameters of the air which can be used as the source of water. The relative humidity (Φ) represents the ratio of the partial pressure of water vapor (P_w) to the saturation pressure (P_s), while the absolute humidity (ω) represents the maximum amount of water that can be extracted from the air. The relative humidity can be expressed using (Eq. (1)) found in the literature [39, 40].

$$\Phi = \frac{P_w}{P_s(T)} \tag{1}$$

where, Φ represents the relative humidity, P_w denotes the partial pressure of water vapor, and P_s represents the saturation pressure. The relation between relative humidity, absolute humidity, temperature, and total air pressure can be described using (Eq. (2)) found in the literature [40].

$$\Phi = \frac{\omega P}{(0.622+\omega)P_s(T)} \tag{2}$$

The dew point temperature (T_d) can be determined from (Eq. (2)) by solving for T at $\Phi = 1$ for given air pressure and absolute humidity. The water vapor saturation pressure (P_s) at any temperature (T) can be described using (Eq. (3)), while the total air pressure (P) can be described using (Eq. (4)) found in the literature [40].

$$P_s(T) = 610.94\exp\left(\frac{17.625T}{243.04+T}\right) \tag{3}$$

$$P = P_a + P_w \tag{4}$$

Total air pressure (P) is the sum of the partial pressure of dry air (P_a) and the vapor pressure of water in the air (P_w). The moist air enthalpy can be described using (Eqs. (5)–(7)) given in the literature [40].

$$H = H_a + \omega H_{wv} \tag{5}$$

$$H_a = C_{p,a}T \tag{6}$$

$$H_{wv} = H_{wv}(0°C) + C_{p,wv}T \tag{7}$$

where H_a term represents the enthalpy of dry air, H_{wv} term represents the enthalpy of the presence of water vapor, and $C_{p,a}$ denotes the heat capacity of air (kJ kg^{-1} C).

4. Principles of adsorption based AWH

Adsorption based AWH is unique in its way that it utilizes the desiccant materials to capture water vapors from the air and shows higher thermal efficiencies as

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compared to the traditional AWH systems. The main advantage is that the desiccant materials can be regenerated by solar thermal energy and the condensation process can occur at ambient conditions [41, 42]. **Figure 3** shows the adsorption based AWH process which consists of two stages. In the first stage, the desiccant material in contact with the ambient air at night which adsorbs the water vapors. In the second stage, the desiccant material is packed into a closed system where a significant amount of heat is provided to regenerate the desiccant material. Due to the regeneration process, the material desorbs the water vapors, and the collected vapors will be condensed into liquid form. With this approach, the AWH can be possible in low relative humidity areas. A lot of advancement has been done in the material designs, and system developments. **Figure 4** shows the dual-stage AWH device mechanism and prototype introduced in the literature [44]. A novelty in this device was that two adsorbent layers were used to improve the water production per day. The latent of condensation from the upper stage was used for the desorption purpose of the bottom stage. With this approach, the thermal efficiency can be improved, and this system can become more suitable for daily purposes. AQSOA Z01, zeolite material was experimentally tested and showed that a prototype can harvest up to 0.77 L/m^2/day with an 18% increase as compared to the single-stage AWH device [44]. The results found that a temperature of 90°C on the solar absorber area can give a maximum water production for AQSOA Z01.

Figure 3.
Adsorption-based AWH process consists of two stages. (a) Adsorption stage (water vapors from the ambient air adsorbed in the adsorbent). (b) Desorption stage (water vapors desorbed from the adsorbent and condensed into liquid form) [43].

Figure 4.
Illustration of dual stage adsorption based AWH device. (a) Mechanism of dual stage adsorption based AWH in which adsorption process occurs during night when ambient air in contact with the adsorbent layer, while the desorption process occurs during day when device is closed, and heat is supplied to regenerate the adsorbent layer. (b) Dual stage AWH prototype consists of convection cover, solar absorber, adsorbent layer, and condenser [44].

5. Progress and perspectives in adsorption based AWH

Adsorption based AWH is a vital technology that can provide cost-effective water in arid areas. The vapor concentration in this technology can be achieved through desiccant materials which ad/absorb and desorb the water vapors from the air [45]. In this context, efficient desiccant materials are a key research priority and various materials have been developed. First, it was believed that the solid desiccant AWH systems can extract enough amount of water but requires a large amount of material which makes these systems very expensive [46]. Also, the operating costs of air blowers to circulate the air for both adsorption and desorption purposes make this system less attractive. However, the development of next-generation MOFs, nano-porous organic materials, and various composite desiccant materials shows great potential for AWH systems. **Figure 5** shows the recent progress in adsorption based AWH systems. Ideal desiccant material should possess the required properties of stability, hydrophilicity, and pore diameter. Adsorption capacities and densities are of great importance in any practical application [51, 52]. The desiccant materials with type IV and type V isotherms are most suitable for this application [43]. During the adsorption process, the materials adsorption capacity should linearly increase with relative humidity, while in the desorption process, the materials desorption capacity should drop steeply with the increased temperature. In this regard, progress has been made and Kallenberger et al. developed a composite material by incorporating the calcium chloride into an alginate-derived matrix [53]. The water uptake capacity of this material was almost linear with relative humidity and when adsorption temperature increases to 65°C, the water uptake capacity drops which shows that the desiccant material can be regenerated at low temperatures. Also, recently developed MOFs show this type of flexibility to harvest enough amount of water at the lowest relative humidity conditions [27, 54]. After the desorption process, the inlet air of the condenser is the outlet air of the desorber. It is worth noting that both the desorption and condensation temperature

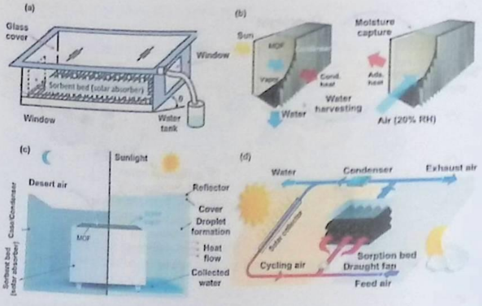

Figure 5.
Adsorption based AWH systems published in the literature. (a) Solar glass desiccant box type system [47]. (b and c) MOFs based AWH systems [48, 49]. (d) Packed columns desiccant matrix based AWH system mechanism [50].

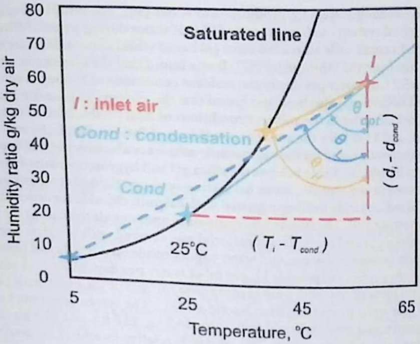

Figure 6.
The optimal condensing temperature on the psychrometric chart developed in the literature [46].

should be carefully chosen to balance the specific water production per day per unit collector area (SWP), and the specific energy consumption per unit mass water production (SEC). In this regard, Tu et al. developed a powerful tool to determine the proper desorption and condensation temperature [46]. **Figure 6** shows the optimal condensing temperature on the psychrometric chart in which the inlet air of the condenser is denoted by I (Ti, di), and the condensation states of the humid air are denoted by the stars on the saturated line. The tangent of the angle (θ) and SEC can be described using (Eqs. (8) and (9)) given in the literature [46].

$$\tan\theta = \frac{T_i - T_{cond}}{d_i - d_{cond}} \tag{8}$$

$$SEC = C_p\left(\frac{\varepsilon_T}{\varepsilon_d}\right) \times \tan\theta + h_{fg} \tag{9}$$

It is noted that when the line through the point I (Ti, di) is tangent to the saturated line, then the angle (θ) is at the smallest value, and therefore the condensing temperature at given inlet conditions for a minimum value of SEC can be obtained at the tangent point. An appropriate heat source and airflow rate can be chosen to find the optimum outlet air conditions of the desorber by using this tool.

6. Energy-efficient desiccant materials for AWH

6.1 Silica gel and hygroscopic salts based AWH materials

Energy efficient materials must have high capacity of adsorbing and desorbing water from the air [55]. Heidari et al. investigated a novel desiccant based evaporative cooling system for production of water [56]. The results showed that the silica gel-based system can harvest up to 585 L of water during a week. Milani et al. investigated a small scale air cooled silica gel based wheel dehumidifier for extraction of water from the atmosphere [57]. It was found that the system can generate more than 5.2 L of water per day in the ambient conditions of Sydney. A simulation model on TRNSYS was also built and found that the system can generate a cumulative of 18.5kL of water in the ambient conditions of Abu Dhabi, 10kL of water in London, and 13.8kL for the ambient conditions of Sydney. Similarly, various desiccant materials based on the hygroscopic salts were also investigated to produce water from humid air. **Table 1** shows the silica gel and hygroscopic salts-based materials used in atmospheric water harvesting systems. Hamed et al. investigated a system based on sandy bed impregnated with calcium chloride for atmospheric water harvesting [59]. The system was exposed to ambient air to absorbs the water vapors in the night and the desiccant material was covered with the glass layer where regeneration process will occur, and water vapors condensed into liquid form. It was found that the system can provide 1 L per m^2 of water per day. Wang et al. investigated a semi open system with a novel composite sorbent of LiCl with active carbon felt (ACF) for water production from humid air [61]. The system was tested at different experimental conditions and found that 14.7 kg, 13.6 kg, and 12.5 kg of water was obtained at conditions of 85%, 75%, and 65% relative humidity, respectively.

6.2 Zeolites based AWH materials

Zeolites are the family of porous crystalline and hydrated aluminosilicates that are widely used as the adsorbents in many applications. These materials can extract water from air at low relative pressures due to their affinity with water [62]. As zeolite materials have a framework structure, a high temperature is required to regenerate and desorb the water vapors. **Table 2** shows the summary of some potential zeolite materials with efficient adsorption capacities. Furukawa et al. studied the zeolite 13X and found that it can harvest water up to 0.40 g/g at low relative pressures [63]. The adsorption properties of Li-X zeolite and Na-X were investigated and found that these materials can be employed to extract water from air [64]. The results found that Li-X and Na-X can extract up to 0.244 g/g and 0.192 g/g respectively. The kind of ion in this type of zeolites not only influences the amount of adsorbed water but also the energy densities and heat of adsorption. Despite the high performance, the energy requirements for desorption purpose restricts the zeolite materials to be used in AWH systems [52].

Adsorbent	Material	Quantity	Water harvesting capacity	Reference
Silica gel	Desiccant wheel		585 L during a week	[56]
Hygroscopic salts	$CaCl_2$/cloth		1.5 L/m^2 day	[58]
	$CaCl_2$/cloth sand	1 kg	2.32 L/m^2 day	[26]
	$CaCl_2$/sand	1 kg	1 L/m^2 day	[59]
	LiCl/sand		90 mL/day, 115 mL/day	[24]
	$CaCl_2$/saw wood/ vermiculite		40–140 mL/kg/day	[60]
	LiCl/active carbon felt	40.8 kg	14.7 L	[22]

Table 1.
Summary of various silica gel and hygroscopic salts based desiccant materials for atmospheric water harvesting found in the literature.

Adsorbent	Material	Water harvesting capacity	Reference
Zeolite	Zeolite 13X	0.40 g water/g zeolite	[63]
	Li-X-Zeolite	0.244 g water/g zeolite	[64]
	Na-X	0.192 g water/g zeolite	[64]
	AQSOA type zeolites	0.1–0.3 kg water/kg zeolite	[65]

Table 2.
Zeolite based desiccant materials for atmospheric water harvesting found in the literature.

6.3 MOFs based AWH materials

MOFs have been researched for their water capture properties and they were found to be highly promising and energy efficient materials. Several members of the MOF family showed unprecedented water uptake property [63]. Specifically, zirconium MOFs made from Zr6O4(OH)4(-CO2)n secondary building units and carboxylate organic linkers showed very interesting properties in water adsorption [66]. MOF-841 was investigated and showed the maximum water uptake and maintained its structure over 80 adsorption–desorption cycles [63]. A similar trend was observed in other zirconium MOF named as MOF-801 which showed a water uptake at 10% relative humidity. Motivated by these results, MOF-801 based device was built and tested in Arizona, desert [49]. The device was consisted of two boxes, the inner box was open and holds the MOF material while, the outer box has a lid. The outer lid was open at night to allow the MOF-801 to in contact with ambient air and hold the water molecules in its pores and then the lid was closed in day and device was exposed to sunlight to regenerate the MOF material. This device was delivered 200–300 mL of water/kg of MOF/day at 20-40oC temperature and 5–40% relative humidity. This device showed remarkable results and proved as a first device in the history to extract water from the desert air. **Table 3** shows the water harvesting capacities of potential MOFs. It can be seen that Co_2Cl_2BTDD material delivered 0.82 g of water/g of MOF under 5-30% relative humidity conditions [68]. It was found that the pore diameter of this material was above the critical diameter for water capillary action which enabled water uptake at the limit of reversibility. **Figure 7** shows the framework structures of some potential MOFs used in AWH systems. The key in all MOFs is the framework structure which allow to trap water from low relative humidity conditions. The water harvesting through MOFs was moved to next level after the development of MOF-303 based device which showed extraordinary results at low relative humidity conditions and also exhibit adsorption and desorption cycles each on the scale of minutes [54]. This device was first tested in a laboratory and later in Mojave Desert at conditions of 10% relative humidity and 27°C and it delivered 0.7–1.0 L of water/kg of MOF/day [54]. It is clear from the discussion that MOFs can be considered as the potential and energy efficient materials for AWH. With these MOFs based AWH systems, not only clean water can be harvested in any climate but also to make this concept more mobile and dispensed [66].

6.4 Other AWH materials

Other adsorbent materials for AWH that have been interested and investigated in the last decade are nano porous super gels and super hygroscopic gels [72–74]. The main factors of these type of materials include the effective capturing of water molecules, high efficiency storage, and fast water desorption abilities under different climatic conditions [28]. **Figure 8** shows the nano-porous super hygroscopic hydrogel employed to harvest water from highly humid atmosphere zones [73]. This hydrogel was made up of Zn and O atoms in a unique ratio of 1:1.1.

Adsorbent	Material	Relative humidity (%)	Water harvesting capacity	Reference
Metal–Organic Framework	MOF-801	20	2.8 L	[27]
	MOF-303		0.175 L/kg	[67]
	MOF-841	5-35	44 wt%	[63]
	Co_2Cl_2BTDD	5-30	0.82 g/g	[68]
	UiO-66	40	0.052 g/g	[69]
	Banasorb-22		0.08 g/g	[70]
	Cr-soc-MOF-1	70	1.95 g/g	[71]
	HSO_3-UiO-66		0.038 g/g	[69]
	IRMOF-1		0.11 g/g	[70]

Table 3.
Metal–organic framework based desiccant materials for atmospheric water harvesting found in the literature.

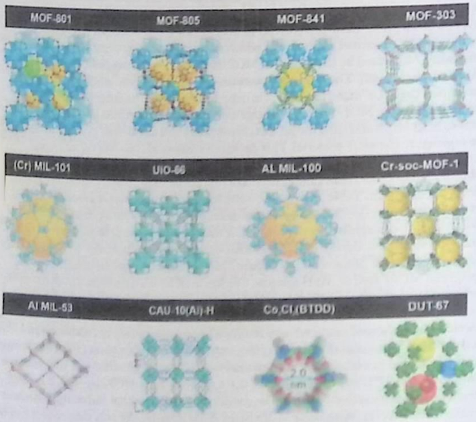

Figure 7.
Illustration of MOFs structures used in AWH systems.

It was found that this synthesized hydrogel has a high-water uptake of over 420% of its own weight. A steep increase in water absorption at high relative humidity of over 80% was shown by the hydrogel which makes it suitable for extraction of water from the humid air. The hydrogel showed the excellent stability for more than 1000 absorption/desorption cycles. It was concluded from the calculations that the absorption cycles of 15 min and desorption of 5 min could give the

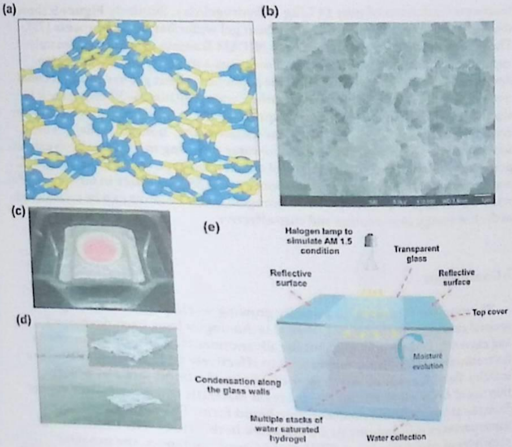

Figure 8.
Nano-porous super hygroscopic hydrogel-based AWH. (a) The hydrogel is made up of Zn:O ratio 1:1.1 (blue balls for zinc atoms, yellows balls for oxygen atoms). (b) SEM image of the hydrogel showing porous network. (c-d) The prototype developed for the absorption characteristics of the hydrogel by floating on the sea surface. (e) Schematic of the AWH system based on super hygroscopic hydrogel reproduced from [73].

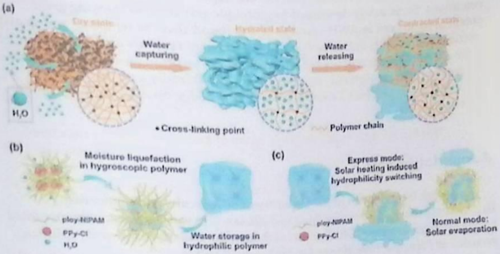

Figure 9.
Super moisture-absorbent gel-based AWH. (a) Illustration of the AWH process (moisture captured by the SMAG and releases water under room temperature). (b) Schematic showing the moisture absorption enabled by the SMAGs. (c) Schematic showing the express and normal modes for water harvesting reproduced from [72].

maximum fresh water of over 14 L/kg of hydrogel/day. Similarly **Figure 9** shows the illustration of super moisture-absorbent gel water harvesting process [72]. The super absorbent gel consists of poly-NIPAM framework which ultimately expands the internal area of the gel and serves as a pathway for water during desorption process. It was found that this super absorbent gel in saturated condition can directly release 50% of the absorbed water within 15–20 min once it is slightly heated to 40oC (denoted the "express mode"). After this phase, the water can be collected via condensation process (denoted the "normal mode"). The super moisture absorbent gel showed two water releasing modes and both can be powered by solar radiation. The super gel-based prototype was also investigated, and it was found that it can produced about 20 and 55 L of water in 60% and 90% relative humidity, respectively. These hydrogels-based systems can be considered as the low energy consumption and cost-effective.

7. Conclusions

The supply of freshwater to a rapidly growing world population is a great societal challenge. In this regard, several technologies have been developed and currently in use worldwide, but the advancements of additional methods for freshwater generation is very crucial to effectively address the global water scarcity. For this purpose, this chapter highlights the importance of adsorption based AWH which utilizes the desiccant materials to capture water vapors from the atmosphere and condenses into liquid form. The important water vapor parameters in ambient air are discussed in this study. The fundamental principles of adsorption based AWH are reviewed, moreover, the progress and perspectives in this technology also explained from the viewpoints of newly developed desiccant materials and the modified AWH systems designs. The study explores the energy efficient desiccant materials which are already employed in AWH systems. From the literature, it was found that the recently developed MOFs are promising due to their flexible nature and tailorable architectures and can harvest water from the atmospheric air at low relative humidity conditions. Some newly developed hygroscopic gels are also showing great potential to utilized in AWH systems. It was found that the temporal and spatial restrictions for AWH and as well as the energy requirements can also be reduced if the appropriate adsorbents are selected. The adsorption based AWH systems ensures no bulky equipment, more environment-friendly and cost effective. Thus, this study presents a comprehensive knowledge on AWH through adsorbent materials.

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Conflict of interest

The authors declare no conflict of interest.

Author details

Muhammad Sultan[1*†], Muhammad Bilal[1†], Takahiko Miyazaki[2,3], Uzair Sajjad[4] and Fiaz Ahmad[1]

1 Department of Agricultural Engineering, Bahauddin Zakariya University, Multan, Pakistan

2 Department of Advanced Environmental Science and Engineering, Faculty of Engineering Sciences, Kyushu University, Fukuoka, Japan

3 International Institute for Carbon-Neutral Energy Research (WPI-I2CNER), Kyushu University, Fukuoka, Japan

4 Department of Mechanical Engineering, National Chiao Tung University, Hsinchu, Taiwan

*Address all correspondence to: muhammadsultan@bzu.edu.pk

† These authors contributed equally to this work.

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Chapter 20

Solar Technology in Agriculture

Ghulam Hasnain Tariq, Muhammad Ashraf and Umar Sohaib Hasnain

Abstract

Promotion of sustainable agriculture is one of the most priority development goal set by United Nations for achieving the food security to meet the ever-increasing global population food demand. Because of extreme importance of agriculture sector, significant technological developments have been made that played pivotal role for sustainable agriculture by value addition in agricultural products and meeting energy demands for machinery and irrigation. These developments include improved cultivation practices, processing units for agricultural products and operation of machinery and irrigation systems based on solar energy. Moreover, the emergence of new technologies and climate smart solutions with reduced carbon footprints have significantly addressed the ever-increasing fuel costs and changing climate needs. PV based solar irrigation pumps and agricultural machinery is typical example of this. Because, awareness of these technological development is essential to overcome energy issues, availability of energy to perform agricultural activities for sustainable agriculture at farm level and socioeconomic uplift of farming community to meet food requirements needs in the future. Therefore, this chapter attempts at providing the introduction of technologies for direct and indirect use of solar energy in the agriculture sector. The typical examples of direct use of solar energy like greenhouses or tunnel farming for cultivation of crops and vegetables and use of solar dryers for drying agricultural products have been comprehensively discussed. Similarly, the solar powered tubewells, tractors, and lights, etc. are few important examples of indirect use of solar energy and have also been discussed in this chapter. The indirect use is made possible by converting solar energy into electrical energy with the help of photovoltaic devices, called "solar cells". Also radio frequency (RF)-controlled seed sowing and spreading machines are discussed, which provide an eco-friendly method. Moreover, comprehensive discussion is made on solar based technologies in general as well regional context in view of their potential to scale-up and to address anticipated issues. The use of photovoltaics in agriculture is expected to be significant contribution in the near future that require urgent planning for the potential benefits and efficient use at the farm level. Therefore, the co-existence of "agrovoltaics" will be essential for the developments of agriculture and agroindustry.

Keywords: Sustainable agriculture, Solar Energy, Agricultural Machinery, Solar Irrigation, Greenhouse, Solar dryers, Agrovoltaics, Agroindustry

1. Introduction

The demand for energy in agriculture has increased significantly to meet the needs of growing population and increasing demand for food. For which not only the already available sources of energy are inadequate and have dwindled because their reserves are nearing to depletion. Therefore, along with other aspects for development in the field of agriculture, the field of research and exploration of new sources of energy is also the focus of interest of agro-researchers. Sun is an eternal center of energy, where solar fuel is being converted into solar energy by the fusion process since the birth of solar system. The use of solar energy is of central importance to meet energy demands. Fortunately, the blessings of Almighty Allah are that the solar energy has many features, which can be used directly and indirectly. For ensuring a sustainable future and addressing the increasingly serious impacts of climate change, especially global warming, developing countries are urgently seeking to switch from traditional energy to renewable energy [1]. Solar energy is abundant, free, and non-polluting; hence, it is considered one of the most competitive choices of all the renewable energy choices [2]. The agricultural sector also uses different methods to take advantage of these different features of solar energy for different applications. For example, the thermal properties of solar energy are used to dry foodstuffs, vegetables, crops, and meat, etc., which is a direct use of it. Drying of these goods is done by direct use of solar energy, but it needs long time which is a waste of time, also it is more likely to be contaminated with dust, malnutrition, food, insects and flies. In addition, unpredictable climate changes, such as wind and rain, can cause serious damages. In modern times, a variety of solar dryers are used for such direct use of solar energy. For the last few decades, solar energy has been used in various ways after converting it to other forms of energy such as chemical energy and especially electrical energy for various services and research has been given much importance for improvement of the conversion methods to capture solar energy. The conversion of solar energy into electrical energy "soletrical energy" has greatly increased the use in various spheres of life. Much research is being done in the field of agriculture for use of soletrical energy. And its use is sure to not only alleviate energy shortages for a variety of purposes, but is also a cheap, easy, unlimited and widely available source of energy on the whole earth throughout the year. The use of this soletrical energy for water pumping, lighting, pesticides spray, and various types of machinery such as tractors, etc., is being innovated day by day in agriculture. But utilization of solar energy in agriculture in this way is still limited, lot of awareness and research is required to be beneficiary of this blessings and hope of future energy requirements.

This chapter includes the awareness of solar energy and potential role of solar energy in the development of the agricultural sector and agroindustry. To avail the benefits of solar energy and consume it to perform various agro-affairs through different applications are discussed in this chapter. Moreover, research done so far to improve the agricultural sector through its use in various ways is also covered in this study. This study will provide coordination between energy researcher and farmers to utilize solar energy with its different characteristics.

1.1 Solar energy

The solar energy is a solar or sun fuel generating at the sun spreading everywhere in the universe and all planets of solar system rely on it. This is also named as clean energy, green energy, alternative energy or sustainable energy. This is the origin of most of the energy sources on earth. The solar energy coming from the sun is in the form of radiations of a range of values. Most of solar energy is captured in the interstellar space and only a small part of solar energy reaches on the earth. But this small quantity of solar energy reaching on earth surface in only one hour is still higher than the energy generated by all other available sources including hydro, nuclear and fossil fuels etc. At the sun about 4,000,000 tons of solar fuel is converted into energy per second, which is so huge comparatively to the conversion ability of a

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1000-MW nuclear power station on earth having the capacity of converting only 0.130 Kg of nuclear fuel into energy in one year. The earth receives about 1366 watts per square meter from the sun, generally which varies with latitude [3]. All the accumulated energy in any form in the earth is because of solar energy, i.e., fossil fuels consisting of natural gas, oil and coal depends directly or indirectly on it. Moreover, all energy reserves are nearly equal to solar energy got from sun only in 20 days. Solar energy is such a fuel which will be lost with the universe. Utilization of solar energy is not a new concept or thinking, human being is utilizing this energy since its birth. Solar energy consists on a spectrum of range of wavelengths of radiations having different energies but most of the solar energy reaches on the earth surface consists on visible light and infrared light as shown in **Figure 1**. Although ultra violet part of this solar energy spectrum is higher in energy strength but lower in intensity. The more intensive part of this spectrum lies in visible part ranging from ~400 nm to 700 nm. Each part of this spectrum has its importance related to applications, i.e., white light for visible purpose lies in the part of solar spectrum 400 nm to 700 nm.

1.2 Assessment of photovoltaic power potential

The assessment of solar energy available in a particular region of the earth is necessary to further harness the source. Because, sustainable and affordable energy supply has strong correlation with the socioeconomic development of any country [5, 6]. Therefore, G20 countries that includes Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Republic of Korea, Mexico, Russia, Saudi Arabia, South Africa, Turkey, the United Kingdom, the United States, and the European Union consumes about 80% of the total energy. Most of the global energy requirements are meet from nonrenewable fossils fuels such as coal, oil and gas. Only, 9% energy requirements are meet by wind and solar energy globally for electricity generation. The global power mix trends of the year 2019 reveals that the increase in solar energy among other renewable sources is 2 i.e., about double than the addition of wind energy in a particular year [7].

The estimation of solar energy potential depends on many factors among the land cover is a major factor in the selection of a suitable area for solar PV generation installation. Direct solar resource is either estimated based on the Diffuse Horizontal Irradiance (GHI) or the Direct Normal Irradiance (DNI). However,

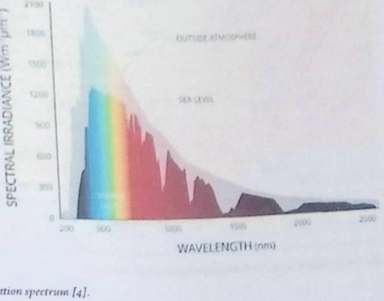

Figure 1.
Solar radiation spectrum [4].

actual solar potential for a region should be assessed by considering geographic, technological and economic potential. Because all the energy reaching to the earth surface cannot be harnessed due to geographically restricted areas, technological limitations due to limited efficiency of solar modules and energy production cost. For example, technological development directly determines the efficiency of the solar power transition. Initially, the PV modules efficiency of monocrystalline solar cells was 15% in 1950 which has now increased to 28% and polycrystalline reached 19.8% [8]. Similarly, governmental policy plays an important role in solar PV generation operation. Therefore, for a comprehensive solar energy potential analysis technological potential, economic potential, and other factors should be considered in addition to the solar energy resource. Researchers are assessing the global solar energy potential by considering these factors. For assessment of the solar potential of 147 countries, the data of Global horizontal irradiance (GHI) air temperature, PV power production potential, Index of seasonal, levelized cost of electricity and economic was used in GIS environment. In addition, some auxiliary data like terrain characteristics, built-up areas, population clusters, tree cover density, land cover and water bodies etc. data was also used to assess the technical potential for solar energy.

The Global Solar Atlas is prepared by Solargis that provides the easy access to solar resource and photovoltaic power potential data globally. Global Solar Atlas 2.0, is a free, web-based application developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). Maps and GIS data are available for 147 countries on online resources (**Figure 2**).

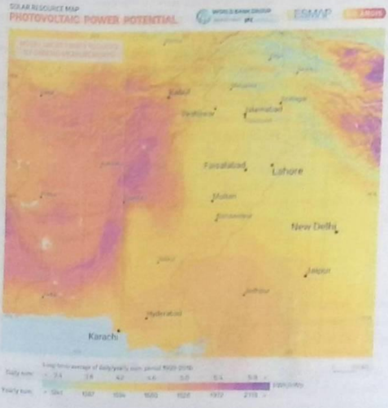

Figure 2.
Solar power potential of Pakistan, https://globalsolaratlas.info/map [7].

The direct solar radiation, having potential of concentrated Solar Power (CSP) and photovoltaic (PV), ranges 5–5.5 KWH/m^2 /day for more than 300 days a year in Southern Punjab. The range in almost all areas of Punjab is 4–6.5 KWH/m^2 /day [9].

2. Scope of solar energy

Climate change is caused by the human's activities relating to energy uses, as carbon dioxide emission is increasing 1.3% annually for the duration of 2014–2019 [10]. Meanwhile, the energy sector taking the responsibility by supporting the policies in technologies and renewable technologies are leading the energy market globally for new energy generation capacity [10]. The year 2020 was a best year for photovoltaic and wind energy market with almost 115GW and 71 GW were added respectively [11, 12]. However, the pace of world's energy transition from traditional fossil fuels to these renewable technologies is far from alignment with Paris Agreement [10]. Although 90% of total electricity energy will be generated with renewable supply by 2050, for which 63% of total electricity needs will be supplied by wind and solar photovoltaics [10]. Solar photovoltaic installed power generation would reach to 14000 GW by 2050 [10]. Solar energy and solar photovoltaic are attractive candidates to fulfill the electricity needs for domestic utility and to run electric vehicles, also cooling and heating requirements.

2.1 Solar technologies

Solar technologies are in common use in simple forms like drying in sun and basking in sunshine since the birth of earth, and people are using some other simple solar technologies including solar water heating and solar cookers by consuming direct sunshine or solar energy. The global solar PV market has rapidly grown by 50% over the past decade [13]. During 2011, more than 29 Giga Watt (GW) new solar PV industry was installed worldwide which was 70% increase compared to the year 2010. Global PV capacity exceeded 69 GW with 70% installed in European countries. During 2017, close to 73 GW of solar capacity added worldwide [7]. Since last few decades, solar energy is being used by converting it into electrical energy with the help of devices called solar cells or photovoltaic devices. These devices are now set up on the hope to fulfill the energy needs and becoming a technology ladder. Another energy converting device is thermocouple which consists on a pair of semiconducting wire with one end connected and other ends are free and when connected end side heated with solar energy than a potential difference is appeared across free ends. Under ordinary sun light efficiency of thermocouples is very low but concentrated sun energy can increase the efficiency of thermocouples. Solar cells convert directly sunlight energy to electricity while thermocouple convert heat from sunlight into electricity [3]. A schematic flow chart of solar energy utilization via different ways is shown in **Figure 3**.

2.2 Solar Technologies in Agriculture

Technology at agricultural farms is changing and improving rapidly. These developments are improving the farm machinery and equipment, farms facilities and buildings, both for crops and animals at farms. As we all know solar energy is the largest and cheapest energy resource on earth. Solar energy can easily fulfill energy provision and supply at agriculture farms. Various solar energy absorbing devices and systems have been developed and are in work for agricultural

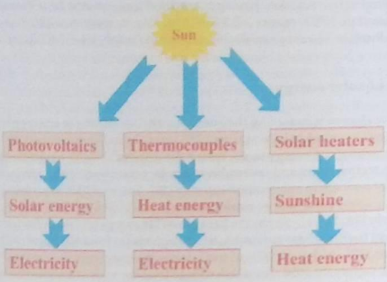

Figure 3.
Utilization of solar energy via different ways.

applications. This includes solar thermal and electric devices such as solar spraying machine, solar greenhouse heating, solar crop dryers, solar water pumps, ventilation for livestock, solar aeration pumps, solar electricity etc.

- **Solar PV operated water lifting/pumping system:**

Solar PV pumping systems are quite helpful to operate the pressurized irrigation system. Specifically, solar pumps may be useful as water lifting devices in irrigation canals and also to evenly distribute water in those areas where traditional water systems could not have access, such as in the elevated hilly lands.

- **Solar spraying and seed sowing machines:**

The solar pesticides sprayer machine is designed for small farmers to improve their productivity. They can easily carry and handle these machines with rechargeable batteries and direct solar illumination options. Mostly pesticide spraying activity is done in the day time, so these spray machines could be used by directly capturing solar energy, which prevents the installation of batteries in these machines. Also, solar powered seed spreading and sowing machines introduce a simple and convenient way of seeds spreading and sowing to small fields, and also in those areas where traditional machinery could not be available. It will be more useful for small farmers and agrarian society. Thus, solar-powered automatic pesticide sprayer and seed sowing machines will facilitate farmers to leave the heavy-duty machines and also provide easy access to work in remote areas of the countryside where general machinery is not readily available [14]. Today radio frequency controlled solar sowing machines are also designed to provide farmers eco-friendly sowing and spreading of seeds. These RF solar controlled sowing machines work with the help of blue tooth, which sow the seeds at controlled depth and distance between seeds [15].

- **Solar crop drying:**

One of the applications of solar energy in agriculture is a solar drying system which is based on variety of options. Solar dryers are available different shapes and structures. Different types of solar dryer are available for various applications, which is used for drying of agricultural products like potatoes, grains, carrots and mushrooms. Depending upon heating arrangement active dryers and passive dryers are two main types. In active solar dryers, external means are used for solar energy heat transfer, like pumps and fans are used for solar energy flow from solar energy collector to crops drying beds, while passive dryer heat is circulated in natural way by wind pressure or buoyancy force or with the combination of these both [16].

- **Solar greenhouse heating:**
Generally, greenhouses around the world use sunlight to meet their lighting needs for photosynthesis, but they are not ready to use the sun for heat. Rather, they rely on conventional energy sources, such as oil or gas, to produce greenhouse temperatures for winter plant growth. However, solar-powered greenhouses (SGHs) are built to use solar energy for both heating and lighting. Also, these greenhouses reduce the damage caused by excess solar energy from the ambient to the greenhouse during hot sunny periods. A controlled environment is available in these SGHs.

- **Solar powered tractors:**
Tractor is a fundamental machinery in agriculture, which made the farming much easier and increased the crops yield and production. Tractor converted the agriculture farming into agroindustry by performing lot of functions with the help of variety of tools and equipment. Usually, tractors consume oil to run and work, which increases the budget of farming also cause the pollution in atmosphere by producing carbon dioxide during combustion. Solar powered tractors became good option which could work directly under the sun by consuming solar energy through PV system in day time and also could continue working in night time with the help of utilizing energy stored in batteries. Although solar powered tractors are in preliminary stage of development but results are hopeful for bright agriculture future [17].

2.2.1 Solar machinery and tractors

Tractor is a most important and central technology and machinery at any agricultural farm. A tractor provides power to perform many tasks, including plowing, seeding, planting, fertilizing, spraying, cultivating, and harvesting crops at farms. Tractor are also used for transporting crops and materials at farms and market. Modern agricultural developments and to increase production to accomplish the needs of human being best farming can be done by using multifunctional compact tractors. Tractors have great social and economic impact on agricultural activities.

Commonly tractors use diesel oil as an energy source. Solar machinery and tractors use solar energy converted in to electricity. One way of using solar energy in form of electrical energy is by using solar panels fixed on machinery or tractors, a schematic diagram is shown in **Figure 4**.

Another way of using solar energy is converting it into electricity at solar power station and charging the batteries of tractors. But in this way energy stored in batteries of a solar electric tractor is very small and a tractor could not work for a long time with a single charging of batteries at solar power station. A challenge for solar electric tractors working in the fields is that the energy density of batteries is low which reduce the working efficiency of tractors. Also charging time of batteries is comparatively is large so exchangeable batteries idea could be used to run tractors for long time [18].

2.2.2 Solar irrigation

Irrigation is a basic need for the crops to grow that play to meet the global food demand. Irrigation demands for crops can be meet by three different sources

Figure 4.
Schematic diagram of solar powered tractor [18].

categorized as green water, blue water and non-renewable groundwater. Green water refers the use of effective precipitation for crop growth that is stored in the soil root zone and blue water to the surface freshwater available in rivers, lakes, reservoirs and the groundwater. Agriculture sector is the major water consumers in the world and accounts for approximately 70% consumption of fresh water [19]. An estimated 67% of the world's crop production still comes from rainfed agriculture [20], where crops requirements are fulfilled from the water held in the root zone of soil. Moreover, the large solar energy potential i.e., more than 6 kWh/m^2 and existence of underground water potential make the solar irrigation well suited for arid and semi-arid regions.

In Asia, especially Pakistan, China, India, and the United States account for 68% of fresh water withdrawals for irrigated agriculture, out of which ~34% is consumed by India only. In Pakistan and India, about 37 million electric and diesel tubewells have been installed in the irrigated area. Therefore, there is great potential to convert these tubewells on solar energy. In Pakistan, there is a 2,900,000 MW solar energy potential due to its geographical location with more than 300 sunshine days, 26-28°C average annual temperature and 1900–2200 kWh/m^2 annual global irradiance [9]. The southern part of Pakistan where annual Direct Normal Irradiance (DNI) is above 5 $kWh/m^2/day$ which is ideally suitable for photovoltaic technologies for irrigation. In Pakistan, about 1.1 million tubewells exist out of which 0.8 million are diesel operated and 0.3 million are electric. The use of tubewells have increased in Pakistan because the surface water supplies are not sufficient to meet the irrigation requirements. Therefore, significant withdrawal is done from the groundwater resources that ranks Pakistan at 4th in the world. Overall, at global scale, estimated groundwater abstraction ranges between 600 and 1100 $km^3\ yr.^{-1}$ [21]. For the year 2000 the reported abstraction rate and estimated groundwater depletion per country with range of uncertainty of India, United States, China and Pakistan is given in **Table 1**.

Country	Abstraction (km^3 yr^{-1})	Depletion (km^3 yr^{-1})	D/A (%)
India	190 (±37)	71 (±21)	37 (±19)
United States	115 (±14)	32 (±7)	28 (±9)
China	97 (±14)	22 (±5)	22 (±9)
Pakistan	55 (±17)	37 (±12)	69 (±48)

Table 1.
Reported groundwater abstraction rate and estimated groundwater depletion per country with ranges of uncertainty for the year 2000 [21].

Significant withdrawal of groundwater shows the importance and the potential of solar energy in irrigation as a substitute of fossil fuels and ultimately providing an environmentally sustainable solution to address the climate changes. Therefore, solar based irrigation can provide a sustainable solution for groundwater pumping which otherwise requires expensive and unreliable energy. Solar powered tubewells have several advantages over traditional systems. For example, diesel or propane engines require not only expensive fuels but also create noise and air pollution. Moreover, the overall initial cost, operation and maintenance cost, and replacement of a diesel pump are 2–4 times higher than a solar photovoltaic (PV) pump. Therefore, solar water pumping system is a cost effective, environment friendly and have low maintenance solution that makes it ideal system for pumping groundwater particularly for remote locations.

Solar energy can also be used for pumping water from the storage ponds to irrigate the crops. However, solar irrigation is coupled with the High Efficiency irrigation Systems (HEIS) for potential use of available water. Because, it is believed that an economics of solar-powered pumping systems can only be justified, if it is properly designed and linked with high-efficiency irrigation systems such as drip, bubbler, sprinkler or bed and furrow irrigation methods. For example, recently, in Pakistan, solar coupled drip irrigation systems have been installed on 21,255 acres during three years (2016–2017 to 2018–2019) [22]. Moreover, promotion of high value Agriculture through HEIS envisages installation of solar systems on 20,000 acres, especially the water scares and saline groundwater areas. Therefore, there is great potential to adopt the innovative solution for the areas where the solar system have been installed due to limited water availability and saline areas. Moreover, there is increasing trend in farmers that can be observed to use these solar pumps f surface irrigation in the plain areas. Moreover, these solar pumps are used to irrigat limited lands of farmers. Therefore, after fulfilling the irrigation requirements the energy can be used for other purposes at farm level. However, there is little evidence to use this available energy where option to connect with the grid is not available. Grid connected solar pumping system is being considered economically viable in the rural areas. For example, a study shows that Levelized Energy Cost (LEC) of the grid-connected SWPS through Life Cycle Cost (LCC) is 4-54% less than the off-grid system depending on the size of the pump [23]. Therefore, it is necessary to provide the alternate utilization of the available energy of solar pumping system for better capacity utilization and economic viability, especially for larger solar pumping units.

Solar water pumping is based on photovoltaic (PV) technology that converts sunlight into electricity to pump water. The PV panels are connected to a motor (DC or AC) which converts electrical energy into mechanical energy. This mechanical energy is used to operate a pump to pump out the water from the ground. The capacity of a solar pumping system to pump water is a determined on the basis of head, flow, and power to the pump. The water pump will draw a certain power which a PV array needs to supply. A typical solar pumping system comprise of a pumping unit, solar panels, inverter, PV mounting structure and foot valves etc. The details of the solar pumping system components and its design can be found in literature [24, 25]. Solar water pumps may be categorized as submersible, surface, and floating water pumps. Submersible pumps are preferred to extract the required quantity of water from deeper depths. However, surface pumps are useful to extract water from the shallow groundwater aquifers. The temperature beyond 25°C decreases the solar output. The dust accumulation also decreases the PV panels efficiency. If a sprinkler cleaner/cooler is not installed then it requires the additional 25–30% PV panels to accommodate the dirt and temperature effects. However, it depends on the air quality conditions of the region. The use of a sprinkler for dust removal and reducing the temperature effects has been found to improve PV solar panel performance by 7–9%. Moreover, solar powered pumping systems efficiency can be increased up to 20% by manually tracking the solar panels. The use of automatic sun tracking improves the pump efficiency but increase the system cost considerably [25].

2.2.3 Solar dryer

Preservation of crops to keep them without rotting and decomposition for long time is essential activity in agriculture. It is required to keep them fresh and nutritious to carry them from fields to consumers. This process of preservation may be from domestic to industrial level depending upon farm size and crops distribution strategies. Different preservation methods include freezing, canning, drying and dehydration. Among these, drying of crops and food is simple and easy method which can work at any temperature and environment. Drying is an easy way to remove moisture from crops and food products in order to keep them with desired content of moisture. It also extends the storage life and enhancement of quality for long time. Basically, drying involves some heating process to vaporize moisture from crops and food products kept in dryers. In earlier time, drying was done by putting crops in open sun, but this method was more likely to be contaminated with dust, malnutrition, food, insects and flies. Thus, from last few decades, many sophisticated dryers are used to remove moisture from foods and crops. Main parameter to control is the temperature of crops which is done by providing certain amount of flow of heat. This heat can be provided by hot air blow through the crops, which may be very costly set up. Fortunately, solar radiations are better source of heat, and solar thermal energy can be used for drying purpose to dry crops, foods, vegetables, grains and any other crops' products. These solar dryers are made in different shapes, sizes and structures to enhance their activity. In these solar dry Different types of solar dryers are in practice for various applications depending on method of heat transfer, their geometry and structure, such as [16];

i. Active dryers

ii. Passive dryers

iii. Integrated dryer

iv. Distributed dryer

v. Mixed mode dryer

vi. Solar cabinet dryer

vii. Green house dryer

Most of these solar drying systems either active or passive can be identified in further three sub-classes of solar dryers [26];

- Direct (integral) type
- Indirect (distributed) type
- Hybrid (mixed mode) type

A most common solar dryer is based on racks design attached with a solar collector, which can collect solar energy in higher amount and can achieve higher drying temperature in result. Solar collector could be a simple black box managed with a transparent cover. Natural convection or an ordinary solar fan could be used to flow the hot air from solar collector to the crops placed on the racks as shown in the **Figure 5**. In agroindustry for large scale applications mechanized solar dryer is used, which is an active dryer type, in which solar heated boilers are used to heat the air, and forced to by fans to approach the crops' beds [28].

2.2.4 Solar fertilization

Fertilizers have central role in the modern agriculture to increase the yield of crops. For fertilizers production ammonia is one of the most important chemicals, which is produced through a well-known Haber-Bosch thermochemical process. By this process 140 million tons of ammonia is being produced per year. This ammonia production consumes large amount of energy nearly 2.5 exajoule per year. To run the process hydrogen is obtained from methane which results 340 million tons of CO_2 per year [29]. Due to huge costs for establishment of plants, centralized production of ammonia with <100 plants worldwide are in function. For better utilization of fertilizers decentralization of traditional fertilizers is compulsory. To overcome these hardens solar energy-based fertilizations is a good option. Solar energy can convert dinitrogen into such nitrogen products which became nutrients for crops. Such

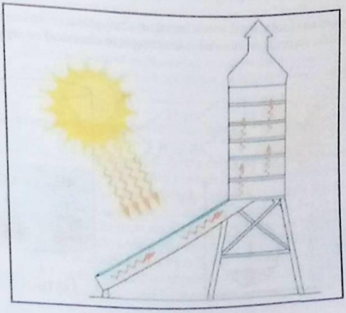

Figure 5.
Indirect solar dryer based on solar collector, racks and chimney [27].

nitrogen products produced by the solar energy are called solar fertilizers. The possibility of producing solar fertilization at country's level may be able to reduce cost of nitrogen based nutrient production by minimizing costs of transportation across the international borders. Also, it will provide employment to jobless workers at country level. Organizing solar fertilizers in developing countries will improve agriculture in remote areas of each country and farmers could become comfortable and satisfied. Above all solar fertilizers will reduce and cut off methane consumption and carbon associated threats to environment. Solar fertilization production is simply based on solar energy, water and nitrogen from air to produce nitrogen-based fertilizers near or at the farms, which also an eco-economic advantage. Management of these solar fertilizers will reduce ammonia use. A study revealed that 250 petajoules of energy/year could be saved by reducing10% use of ammonia or urea-based fertilizers [30].

The developments of solar fertilization need good and reliable strategy for dinitrogen fixation at ambient temperature. These developments can be made by the help of bioengineering, and catalysis research under precise conditions and approach [31, 32]. Such fixation of nitrogen in solar fertilizers can be accomplished by efficient electrochemical and photochemical natural process, which are expected to have significant lower concentration of nitrogen. These solar fertilization with lower concentration is characteristically safer and enable better nutrient managing [33]. The solar fertilizer production is similar in some aspects to the solar hydrogenation production, as light absorption, catalysts' reaction and energy transfer from absorbent material are involved in both processes. However, solar fertilizers would be integrated with agriculture farm infrastructure and for different application. Some of the key aspects of such processes required for production of solar fertilizers include capture or absorption of solar energy, catalysis reaction and separation process for production of solar fertilizers [34–38]. In this whole process of solar fertilizer production sun energy from sun light or solar fuel is absorbed by solar cells and/or photocatalytic particles which provide a potential to initiate an electrochemical reaction to convert dinitrogen, oxygen and water in to nitrogen products like nitrates and including ammonia in aqueous solution schematically shown in the **Figure 6**.

- **Absorption of solar energy**

As production of solar fertilizers is based on absorption of utilization of solar fuel by solar energy from sun and converting it to chemical energy by two

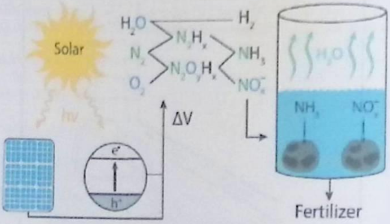

Figure 6.
Schematic diagram of solar absorption, catalysis reaction and separation process for solar fertilizers' production [29].

ways; *i*, *direct absorption* of sun light in a photocatalysis process (photochemistry), and *ii*, *indirect absorption* of sun light in a PV-electrolysis (photovoltaics and electrochemistry). A third hybrid approach (direct + indirect) is photoelectrochemistry in which electrical biasing is required absorption of sun light [37, 38]. These solar fuel technologies have good motivations for production and utilization at decentralized remote locations or at agricultural sites as compared to centralized huge industrial production.

- **Catalysis reaction**

  After absorption of the solar energy the conversion of molecular dinitrogen, oxygen and water is the central process of production of solar fertilization. For this a catalyst is required to dissociate triple bond of dinitrogen at favorable temperatures. Most approaches for this nitrogen dissociation have focused on chemical reduction of nitrogen to produce ammonia. For nitrogen reduction one of the best catalysts is based on carbon which shows an efficiency of 5% for electrical-to-ammonia in an aqueous solution [39].

- **Separation process for production**

  The chemical separation process for generation of reactants and convert the effluents to a fertilizer is an important step of solar fertilization technology. Because nitrates, ammonia and urea are water soluble which make a challenge for separation and concentration of products. Aqueous electrolytes are used in many electrochemical techniques for this separation process. Generally, these separation process require sophisticated techniques and processes for particular catalyst. This separation can be moderated with supported catalysts [40].

2.2.5 Solar dairy farms

Milk value chain from small dairy forms to market could be improved by using solar cooling technology. Milk cooling technology is costly and mostly small dairy farm (SDF) owners have lake of facilities for this purpose. Usually, these SDF owners are associated in dairy cooperatives which are responsible for managing to collect the milk from member owners and then supply collected milk to market or dairy plants. Lake of facilities of milk cooling in hot weather under warm climate conditions can lead to high bacterial contamination in milk. Solar dairy farming is based on solar technology.

- **Solar freezers or refrigerators at dairy farms**

  An emergency and simple way of saving milk is by using ice or freezers for cooling purpose. But, most of SDF exists in remote areas where transmission lines are not possible. In these areas solar powered freezers is a good option. Ice produced in these freezers could be used in milk cans for a better and effective cooling. Different institutions are working for developments of solar dairy farms specially for milk cooling. At Institute of Agricultural Engineering of the University of Hohenheim a solar milk cooling system has been designed which is based on the utilizations of ordinary milk-cans in Tunisia. In these designed solar dairy farms solar freezers are being used to produce ice for milk cooling. These milk canes can preserve milk for six to sixteen hours depending on amount of ice put in milk cans [41]. These solar dairy farms have great potential to improve dairy values and more efficient in remote and off grid areas by using environment friendly and clean energy. **Figure 7** dairy farmers' comments and observations on the impacts that those farmers experienced due to use of solar technology [41].

- **Solar heating for steam generation**

  Sterilization process is an important activity at dairy farm for which low temperature steam is used. Parabolic trough collectors are commonly used to generate steam and other high temperature applications. At dairy farms solar water heater could be installed to raise the water temperature from 27–67°C [42]. A lot of furnace oil and other fuels could be saved by using solar heating at dairy farms.

2.2.6. *Solar greenhouse production*

All crops at agriculture farms needs proper environment including moister in air, temperature and light intensity. These parameters have great impact on for crops growth and yield, but we have not any control on them. All these parameters are controlled and determined by the nature, which are never remain constant and all time favorable. A lot of variations exist in environment and weather, sometime favorable and sometime very bad for crops. For continuous production at agriculture farms a favorable environment and conditions are required. Such a proper environment and promising conditions could be provided at solar greenhouse. Solar greenhouse is a covered structure where crops and vegetables are grown under favorable climate conditions and proper environment for the growth and roduction of plants. In greenhouse a controlled sunlight is managed for photosyn-esis and also an adequate temperature is maintained suitable for plants whether tside is hot or cold. Vegetables could be grown throughout the year in these solar

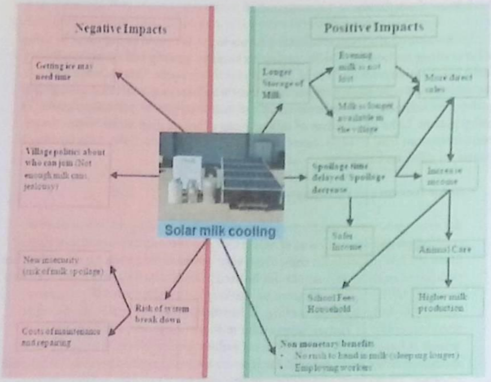

Figure 7.
Effect of small-scale solar milk cooling [41].

greenhouses. In these greenhouses solar energy is collected and stored in many ways and therefore they differ in designs. There are many parameters that effect the growth of plants in solar greenhouses. Among these parameters' intensity of sunlight, temperature of greenhouse, temperature of surroundings, humidity of greenhouse and surroundings, nutrients and carbon dioxide etc. Greenhouses provide such an environment to plants that they can grow in controlled conditions and optimized values of all these parameters.

Sunlight intensity

Sunlight, water and carbon dioxide are essential ingredients to produce carbohydrate and oxygen in photosynthesis process occurred in the chlorophyll of chloroplasts of plant cells. Initially chloroplast is responsible of absorption of sunlight and then for following chemical reaction.

$$H_2O + CO_2 + Sunlight \rightarrow Oxygen + Carbohydrate \quad (1)$$

These carbohydrates are used in the growth of the plants. In the respiratory process the energy is released which is used for the growth of plants and fruits. Better control of sunlight is responsible of efficient photosynthesis process and carbohydrate production. Sunlight intensity varies from beginning of day to time of noon from 0 to 150000 lux respectively. It also varies for weather difference like in cloudy days light intensity goes lower and some types of plants could not grow appropriately. For low and high sunlight intensity level, the photosynthesis process very much effected and plant's growth and yield are limited. Sunlight intensity is different required for photosynthesis in different plants like cucumber can grow in high intensity of sunlight, while tomato, lettuce and carrot need lower intensity of sunlight. Light intensity can be increased in the regions where light intensity is lower by different methods like by painting the walls and roof of greenhouses. Moreover, additional lighting may be required in the darken days to increase the light intensity as well its duration. For this additional lighting different types of lamps are used which are powered by solar cells.

- **Temperature of greenhouse**

Other than sunlight temperature is another parameter which should be optimum for biochemical reactions in the different types of plants. Temperature of plants surroundings and soil is very much dependent on sunlight intensity, humidity, air velocity and carbon oxide in the greenhouse. Temperature may affect different activities like food and water in root system, transportation of minerals in stems and leaves, and photosynthesis process. Also, for different stages of development of plants like germination, growing, flowering, fruit beginning and fruit reap or maturation, different temperature is required as shown in **Figure 8**.

- **Humidity in greenhouse**

Humidity in greenhouse environment plays a vital role in plants' growth and health, as relative humidity ranging from 30 to 70 percent is perfect for plants' growth, while comparatively higher relative humidity i.e., more than 90 percent is harmful for plants' health as it provides a suitable environment to pathogenic organisms' growth. Solar greenhouses provide controlled humidity in the environment and surroundings of plants growing within the greenhouse, where generally relative humidity between 55 to 65 percent and environment temperature between 20 to 25°C could be controlled.

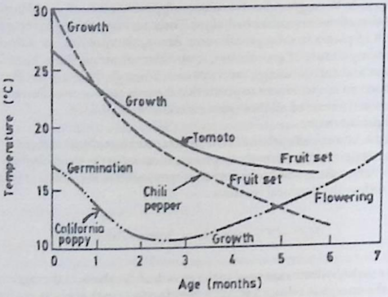

Figure 8.
Optimum temperature at night for growth and production [43].

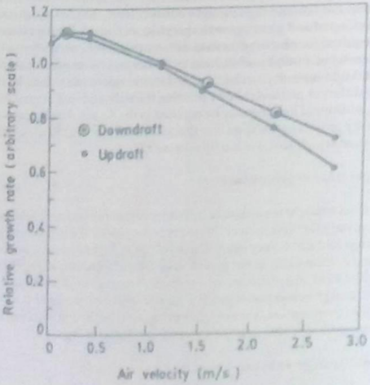

Figure 9.
Effect of air speed on leaf's growth [43].

- **Air transport and carbon dioxide**

Air transport affect the evaporation of water, availability of CO_2, cooling effects etc. so the growth of plants is affected. The air speed the plant's transpiration and

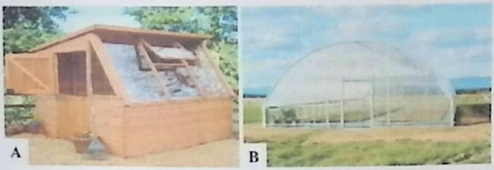

Figure 10.
(A) Shed type solar greenhouse; (B) Quonset solar greenhouse [44].

water vapors from plant to outside air, movement of CO_2 for photosynthesis. The air speed effects the plant growth as shown in **Figure 9** that the leaf's growth is effected by increase in air speed [43].

- **Solar powered greenhouse design**

The design of a solar powered greenhouse is different from an ordinary greenhouse in following few aspects;

- Glazing should be oriented in such a way that it can receive maximum solar energy.
- Use different heat storage materials to hold solar heat in winter.
- Use such glazing materials which minimize heat loss.
- Natural ventilation used for cooling in summer.

Two primary solar greenhouse designs are; i, Shed Type, & ii, Quonset Hut [44]. The orientation of shed type solar greenhouse is based on its length side along east to west direction as shown in **Figure 10A** [44]. Its north wall is painted or covered with some reflective material. The Quonset huts do not have any covered or insulated wall. Their structures are so that absorption of solar energy and distribution of solar heat is enhanced. Although insulation of solar greenhouse walls is required to minimize the solar heat losses, as shown in **Figure 10B** [44].

3. Conclusions

Technologies at agricultural farms are improving rapidly to facilitate farmers and bringing innovations in farming business. But this rapid increase of technology dependent agriculture farming required lot of energy resources. Also, the energy consumption increases the production cost of agriculture products. To overcome these energy and cost issues cheaper, easily and abundantly available energy sources are required. Fortunately, sun is a huge source of energy with abundant solar fuel on it, which can last till the life of earth. Thus, the solar energy is the largest and cheapest energy resource available on earth. Solar energy can easily fulfill energy need and supply at agriculture farms. Solar energy-based agriculture farms can easily accomplish energy requirements and reduce cost production. Utilization of solar energy at agricultural farms includes different types of machinery and equipment depending on task to accomplish by using different characteristics of solar energy like heating or converted in some other form of energy, such electrical or chemical. These applications include solar thermal and electric devices such as solar spraying machine, solar greenhouse heating, solar crop dryers, solar water pumps, ventilation for livestock, solar irrigation pumps, solar electricity etc. These solar energy equipped machineries also include radio frequency solar controlled sowing and spreading of seeds. Solar energy is a trustful and reliable source to compensate all requirements of energy for future.

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Author details

Ghulam Hasnain Tariq[1]*, Muhammad Ashraf[2] and Umar Sohaib Hasnain[3]

1 Department of Physics, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan

2 Department of Agricultural Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan, Pakistan

3 Department of Electrical Engineering, Attock Campus, COMSATS University Islamabad, Pakistan

*Address all correspondence to: hasnain.tariq@kfueit.edu.pk

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Chapter 21

Experimentally Investigated the Development and Performance of a Parabolic Trough Solar Water Distillation Unit Concerning Angle-Wise

Fahim Ullah

Abstract

The PTC performance was evaluated at four (i.e., 25o, 35o, 45o, and 55o) different adjusting Angles and it clearly showed that the adjusting Angles is highly significant, affecting the efficiency of the collector. The PTC received mean solar radiation 513 kJ.m-2.hr-1 with the absorbing temperature of the absorber in PTC was noted 123oC, 115oC, and 113oC consecutively the months of the year with the adjusting angles of 25o, 35o, and 45o respectively. Distilled water from the solar water distillation unit was found to improve the laboratory's quality and wash equipment in the hospital. PTC's efficiency noted 26.9%, 26.3%, and 26.1% with the distilled water up to 217, 313, and 343 ml.m-2.day-1 for the adjusting Angles of 25o, 45o, and 35o respectively. From the result, it concluded that to obtain maximum distilled water, the PTC should be set on adjusting Angles of 25o, 35o, and 45o. The average unit price of distillate from the solar still is assessed as Rs. 2.64/L-m2 with a payback period is 365 days. The unit distillate cost is seen to reduce significantly from Rs. 4.92/L to Rs. 1.57/L. It concluded from results that the distilled water of PTC relatively decent quality.

Keywords: Solar energy, Parabolic Trough Collector, Efficiency, Distilled water and Adjusting Angles

1. Introduction

1.1 Background of the study

Most developing countries are in a vital energy crisis [1, 2]. The demand for energy has increased over the years because of the increasing world population and expansion of global industries, especially food and feed. Most of the energy consumption is from power generation, transportation, and industry community sectors [3, 4]. Moreover, most utility energy is taken from fossil oil, gas, and coal. Many developed countries have their policies to find alternative energy.

Energy plays an essential role in the industrialization and economic development of a country. A country will be prosperous if it has sufficient energy resources to fulfill its needs [1]. Besides the available energy resources, countries must work hard to explore and conserving renewable energy resources. The total solar energy received from the atmosphere and absorbed by Earth's oceans and landmasses is approximately 3.85 x 1024 W.yr-1 [2]. The total solar energy coming from the sun is so vast in one year, which is twice about the energy produced from the resource of the Earth's non-renewable, i.e., coal, oil, and natural gas [3, 4]. Pakistan is being located between 23.8o to 36.7o north latitude and 61.1o to 75.8o East Longitude. It is rich in renewable energy resources.

Ahsan et al., [5] attempted to find suitable resources to produce alternative energy such as biomass, solar energy, geothermal, hydropower, wind energy and ocean energy. Nanjing is a city found in Jiangsu, China. It is located 32.06 latitude and 118.78 longitude and it is situated at elevation 22 meters above sea level. It is rich in renewable energy resources. Solar energy has brilliant prospectus at a latitude of 32o which can be utilized for making electricity by photovoltaic (PV) cells, drying of products by solar collectors, water heating and water distillation systems [6, 7]. A total of 174,000 terawatts (TW) of energy reaches the earth at the upper atmosphere to form the incoming solar radiation (insulation) [8, 9]. From this total energy approx. 30% reflected to the atmosphere, and the remaining energy is absorbed by the clouds, oceans and land masses [10, 11]. **Figure 1** shows the incoming, absorbed and reflected solar radiation from the atmosphere. It shows the spectrum of solar light/radiation at the surface of the earth, which mostly spreads across the visible range and near the infrared ranges. Most of the population lives in the areas where the land received the insolation levels in the range of 150–300 watt/m2 per day or 3.5-7.0 kWh/m^2 per day [11-13].

Hydroelectric and thermal solar energy has enormous prospective sources of renewable energy. Energy plays a vital role in the industrialization and economic development of a country [14, 15]. A country will be prosperous if it has sufficient energy resources to fulfill its needs. In addition to the available energy resources, countries must work hard to explore and conserve renewable energy resources. The solar energy coming from the sun is so vast in one year that it amounts to twice the

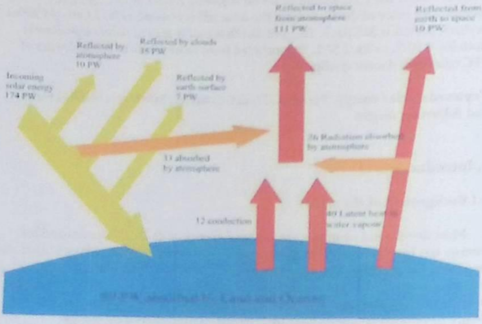

Figure 1.
Schematic diagram of the incoming, absorbed and reflected solar radiation intensity.

energy which is produced from the resources of the earth's non-renewable energy such as coal, oil, natural gas [16, 17]. Renewable energy provides a clean and nontoxic energy source. The key sources of energy are the sun, wind, biomass, waves and geothermal energy [18, 19]. Solar energy can be exploited in the form of thermal energy by using different kinds of solar collectors for different purposes, i.e., dehydration of fruits & vegetables, water distillation and producing electricity [19, 20].

Energy is an elementary need for agriculture and other industries [21, 22]. Different resources, like wood, coal, fossil fuels and nuclear chemicals were used as foundations for energy, but all these sources are getting rare [23, 24]. By using resources like wood, coal and fossil fuels for energy utilization, we are adding significant agents producing while environmental pollution and global warming. Due to high prices and shortages in the future, scientists of the world have established other energy resources called renewable energy resources including solar, tidal, wind and biomass [25, 26]. Wind and tidal energy are present in small areas of the globe while solar energy is present universally. The sun is the eventual source of energy for the earth. Energy from the sun is interminable and green as it does not create pollution and global warming [27, 28]. The sun gives us electro-magnetic particle emission called solar energy and this energy can be consumed for different purposes like the drying of agricultural products, heating buildings, for irrigation purpose and for producing electricity [29, 30]. In the fourth century B.C., different methods were used for getting dried fruits & vegetables, which were very difficult to be performed. The dehydration of fruits & vegetables and other crops dried by open-air sun drying was not satisfactory, because the products became infected with bacteria, rodents, and insects, and worsen quickly due to the high ambient temperatures and relative humidity [31, 32].

1.2 Status of solar energy usage

Figure 2 showed the status of different sources of energy usage in the year 2016 in China. Solar energy is the most promising technology in the world [33]. Energy plays an essential role in the industrialization and economic development of a country. A country will be prosperous if it has sufficient energy resources to fulfill its needs [34]. Besides the available energy resources, countries must work hard for

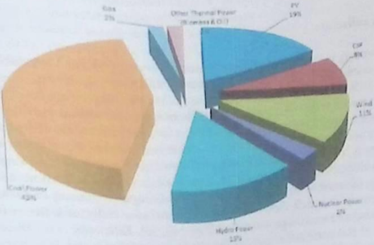

Figure 2.
Status of different sources of energy usage.

exploring and conserving renewable energy resources. The total solar energy received from the atmosphere and absorbed by the earth, oceans and land masses is approximately 3.85 x 1024 W.yr-1 [35]. The total solar energy coming from the sun is so vast that in one year it is twice the energy produced from the resource of the earth's non-renewable, i.e., coal, oil, natural gas [36, 37].

The concept of alternative energy is to develop other resources as a substitute for petroleum and to reduce the central issue of global warming. China and Pakistan import fossil fuels annually, equivalent to 40% of all total imports to fulfill the energy requirements of the country while spending 7 billion dollars. From the survey, it is clearly shown that by the year 2050, energy needs are expected to be three times the current needs in China and Pakistan while supplies are less than inspiring. For the utilization of this incoming solar energy, different kinds of solar collectors were used for various purposes, i.e., dehydration of fruits and water distillation.

1.3 Review of the literature

Renewable and sustainable energy resources are the best substitute for conventional fuels and energy sources in a country's energy security and sustainable developed as well as its minimal environmental impact. China and Pakistan are making attempts to promote and support the utilization of alternative energy and to improvement in energy efficiency. Different researchers have conducted experiments on the drying of different fruits and vegetables, and the desalination process using different solar collectors. The researchers [38–40] found that hot air drying reduces the risk of the development of Alfa toxins in fruits. They experimented with a pilot airflow cabinet dryer with the greatest loss in ascorbic acid. They also concluded that pretreated fruits take a shorter time to dry as compared to controlled fruit. **Figure 2** shows the Status of different sources of energy usage in 2016.

Most of the energy consumption is from power generation, transportation, and the industrial community sectors. Moreover, the most utility energy is taken from fossil oil, gases, and coal. Many developed countries have policies to find alternative energy. Many researchers have attempted to find suitable resources to produce alternative energy such as biomass, solar energy, geothermal energy, hydropower, wind energy and ocean energy. The concept of alternative energy is to develop other resources as a substitute for petroleum and to reduce the central issue of global warming.

1.4 Solar collectors

Solar energy is a well-known process used for drying fruits and vegetables, while it is also usable for other purposes, i.e., water distillation and ventilation, etc [41, 42]. Different types of collectors are used for collecting energy from the sun, but the flat plate solar collector and parabolic trough solar collector are the most appropriate for getting more tracking sunlight for the dehydration of fruits and vegetables and water distillation [43, 44]. Other researchers [45, 46] have reported that drying is the most dynamic process for better quality of fruits and vegetable. The researchers [47, 48] said that the flat plate solar collector is the best method for the heating of water with convective heat flow having an efficiency of 35–45%. Several years of research showed that the flat plate solar collector is better for the use of heating of farm shops, dairy buildings [49, 50]. Efficiency is the important parameter of flat plate solar collector for the heating of water and dehydration of different kinds of agricultural fruits and vegetables [51, 52]. The ability of the collector depends on an optimum combination of temperature and flow rate [53].

Solar collectors can be utilized for different purposes such as the purification and distillation of liquids, the drying of products, the heating of water for various purposes, for lighting at night and for water pumping [38]. The researchers [39, 40, 54] found that solar energy is one of the promising techniques in renewable energy for getting the pure and clean water from potable water resources. There are so many techniques which are used for heated water to produce clean and pure water i. e. solar collector, solar photovoltaic, etc. [55–60]. In this research project, we have designed two solar collectors, i.e., flat plate solar collector and parabolic trough solar collector. Both were used for the dehydration of fruits, i.e., apples, apricots, and loquats, etc., and also for water distillation purposes with the development of a single-axis tracking control system.

Parabolic trough solar collector.

This type of collector is used in solar power plants [61]. A trough-shaped parabolic reflector is used to concentrate sunlight on an insulated tube (Dewar tube) or heat pipe, placed at the focal point, containing coolant which transfers heat from the collectors to the boilers in the power station [62]. In a parabolic dish collector, one or more parabolic dishes focus solar energy at a single focal point, similar to the way reflecting telescopes focuses starlight [63]. The shape of a parabola means that arriving light rays which correspond to the dish's axis will return toward the focus [61]. Light from the sun reaches the earth's surface almost entirely parallel, and the plate aligned with its axis pointing at the sun permits almost all incoming radiation to replicated toward the focal point of the plate [64]. Most damages in such collectors are due to deficiencies in the parabolic shape and lacking reflection. Losses due to atmospheric trickle are minimal [65–111]. However, on a hazy or foggy day, light is diffused in all directions through the atmosphere, which significantly reduces the efficiency of a parabolic dish [1].

Solar energy has brilliant prospects at the latitude of 34o, which can be utilized for making electricity by Photovoltaic (PV) cells, drying of products by solar collectors, water heating, and water distillation systems [5]. The wick type solar collector with load and no-load at the adjusting Angles of 10o, 20o, 30o, and 40o tested in summer and winter. The average yield of distilled water was 2300 ml/m2/day1 in winter and 3400 ml/m2/day1 in summer reported by [6, 7]. The distilled water production was 182 ml/m2.hr. with the difference between glass and sea-water, and the solar system's efficiency was noted 21.3%. They concluded that in 48-hour, the distilled water production increased from 3000 ml/m2 to 3200 ml/m2 by [8, 9]. The solar efficiency still determined with different inclination adjusting Angles of 15o, 30o, and 45o to compare various conventional solar distillation systems' energy determination. The use of polyvinyl chloride material in collectors have increased the efficiency, studied by [10]. The collector's daily output was in the range of 2 to 4 l/m2/day, and efficiency was calculated by 27% tested the flat plate collector at the inclination adjusting Angles of 45o with the horizontal facing due south. They studied the collector from 08:00 AM to 05:00 PM during sunlight hours, and output was increased by 31% evaluated by [11]. The product's output was increased from 2240 ml/day to 3510 ml/day during October to December using the flat plate solar collector with the adjusting Angles of 35o with different parameters conducted by [12].

The basin's efficiency- type solar still was highest in Jun, July, and August up to 75% with solar irradiance, and the output of the basin was 7000 ml/m2.day. It was further studied that the output of a solar still was decreased without using the condenser collector [13]. The solar still plant studied with different tilt adjusting Angles of 15o, 25o, 35o, 45o, and 50o and reported that maximum output was obtained by adjusting Angles of 35o during May. They noted the maximum absorber temperature at 01:0 PM to 02:0 PM [14, 15]. Distilled water is used in various industries, nuclear-powered ships as a coolant, various beverages, Lead-acid batteries, automotive cooling systems, steam irons for pressing clothes and surgical instruments washing, etc. An electric water distillation plant commonly prepares distilled water, but it has a high initial cost and requires electricity.

On the other hand, solar energy can prepare distilled water [16, 17]. Different designs of solar collectors are available that can be used for water distillation. Solar distillation plants can work by the natural water cycle, and it can receive the solar energy to warm the water so that the water boils and evaporates. The vapors are then condensed in distilled water forms as it cools down reported by [18]. The solar collector can be utilized for different purposes such as purification and distillation, dried water heating, heating of water for different purposes, lighting at night, and water pumping [19]. In the solar desalination system, water is converted to steam using the sun's energy, and then these vapors condense as pure water. After the condensing of vapors, it's free of salts and other impurities.

The solar distillation water plant is a cheap and straightforward method to distill or purify water reported by [20]. This plant required solar radiation as heat that can convert water into the vapors form. Therefore, for solar distillation, the 2260 kj.kg-1 energy is required to evaporate the water evaluated by [21].

1.5 Significance of the study

There is a shift record in the adoption of solar technology due to a shortage of electric power. Energy is the primary need nowadays and to fulfill the requirement of people to use solar thermal collectors to overcome the lack of solar energy. Solar thermal collectors convert solar radiance to heat and then this heat is given to a fluid which utilizes this heat to produce distilled water form tape. It was also used for the arm purposes in the buildings to convert water to steam. The performance of solar llectors was a keen factor to use them efficiently for dehydration and water distilla- n purposes. Energy is the input or the heat given to the collectors that are available om the solar radiation daily and to apply for some useful purpose, i.e. water distilla- ion. Efficiencies based on the first law and second law of thermodynamics.

To overcome and maintain the problem of water distillation, researchers indicate the prefer ability of solar collectors' i.e. flat plate solar collector and parabolic trough solar collector are suggested for increasing the yield during the water distillation. The water distilling is the most important parameters during the distillation with the process of solar collectors. Most of the studies focused on the distillation process with the using of flat plate solar collector and corrugated plate solar collector, but few were focused on the design of parabolic trough solar collector and concentrating parabolic collector. Producing of distilled water can be done using solar energy, but there is a need for sophisticated technology for distillation without affecting the quality of produced distilled water. The multistage water distillation process is a well-known process used by many researchers for tap water distillation.

Although a lot of research has been done in this field, there is a gap regarding energy and cost-efficient use of water distillation. A considerable amount of energy is consumed in order to maintain the water distillation process. To fill the gaps in the data, a research program was carried out to experimentally investigated the development and performance of a parabolic trough solar water distillation unit concerning angle-wise; we aimed to get the necessary data to rate commonly used solar collector designs and to identify the required modifications.

1.6 Objectives of the study

The research project was carried out to study the **experimentally investigated the development and performance of a parabolic trough solar water distillation**

unit concerning angle-wise. In the present research study, solar distilled water unit was developed in the form of PTC in the Department of Agricultural Mechanization, FCPS, The University of Agriculture, Peshawar- KPK, Pakistan with the primary objectives of the study are as follows:

- To fabricate the parabolic trough collector (PTC).
- To investigate the development of parabolic trough solar water distillation unit concerning Angle-wise.
- To study the performance of PTC with Angle-wise (Efficiency).
- To compare the quality of prepared solar distilled water with the available distilled water in laboratories.

2. Materials and methods

2.1 Parabolic trough collector

Parabolic trough solar water distillation unit consists of a parabolic reflector, as shown in **Figure 3**. The reflector was made of a Galvanized iron sheet. The sun rays strike on the reflector sheet and then reflect the absorber's one focus point (used for distillation). For constructing the PTC, the focal length was calculated by using two methods. One is the software used to find the focal point, which name as a Parabolic Calculator 2.0 version, as shown in **Figure 4**, and secondly, the Eq. (1), studied by [22], is used to find the focal point of PTC. The cross-sectional area of PTC was calculated using Eq. (2) reported by [23].

$$Y = \frac{x^2}{16\,f} \text{ or } f = \frac{x^2}{16\,y} \quad (1)$$

$$Art = Wrt \times Lrt \quad (2)$$

The absorber consists of a black-painted pipe, which received water from a storage tank and then heated up and converts to vapors form with solar radiation

Figure 3.
General view of parabolic trough solar water distillation unit.

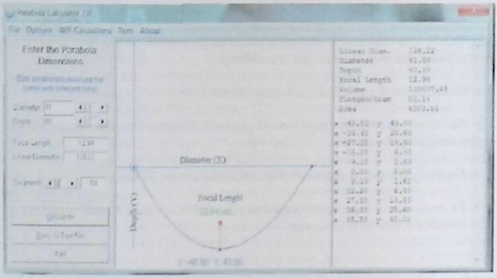

Figure 4.
The dimension of parabolic trough.

intensity absorbance. The absorber area and volume were calculated by the following Eqs. (3) and (4).

$$A_{ab} = \pi \times D_{ab} \times L_{ab} \tag{3}$$

$$V_{ab} = \pi \times r^2 \times L_{ab} \tag{4}$$

Two storage tanks were used in the experiment. One for inlet water, which contained tap water, and the other used for outlet distilled water. The collector is oriented along the east–west axis along the longitude and the altitude of the experimental area. The tilt adjusting Angles of the collector adjusted with an adjustable stand to collect maximum solar radiation [24].

2.2 Solar radiation intensity

The solar radiation intensity is the amount of energy received from the sun per unit time per unit area on the Earth. The SRI was recorded daily, weekly, and monthly with a Mechanical Pyranometer and recorded in Mechanical Pyranograph. Eq. (5) is used to determine solar radiation reported by [25].

$$I_s = 368 \times V_c \tag{5}$$

2.3 Performance of parabolic trough collector

The Performance of the PTC assisted for the solar water distillation unit was evaluated in terms of the quantity of distilled water obtained during a laboratory experiment. The distillation unit (condenser) is attached to the absorber, and it received water vapors from the absorber through the outlet opening-jet. The vapors cooled down to low temperature in the distillation unit to become liquid form. For sea-water distillation, we used this system, and it works well. Still, the scaling effect came after the sea-water passing through the absorber, and also through the distillation unit, it was blocked both systems with the microbes and some other type of micro-organism. Still, we clean both the system after three days using the chemical of concentrated nitric acid to clean that system for all the scaling effect cause.

Efficiency is the ratio of heat available to the collector (input) and distilled water (output). The PTC's performance was evaluated at different adjusting Angles, i.e., 250, 350, 450, and 550 without sun tracking system in a whole day for three consecutive months of the year, 2012, i.e., June to October. The temperature data was also recorded in this experiment. Eq. (6) was used for the efficiency of PTC studied by [26].

$$\eta\ (\%) = \frac{\text{Mass of distilled water (kg)} \times 2260\left(\frac{\text{kJ}}{\text{kg}}\right)}{\text{Solar energy (kJ)}} \times 100 \tag{6}$$

2.4 Testing of water quality

The purity of distilled water was tested with the help of E.C meter (Model No: 4310). Before using the E.C meter, it was calibrated with the standard 0.1 and 0.01KCL solutions, and the S.I unit of E.C meter is expressed in Siemens [27]. When the E.C meter reading is in the range of 0-30μS.cm-1, the distilled water is free from impurities, i.e., Ca, Mg, Zn, and Na. While the reading greater than 30μS.cm-1 means that the distilled water contains impurities in the form ions reported in the literature [28].

2.5 Economic analysis

The procedure described by [29] is utilized for economic analysis of the solar still, and the main factors used in the analysis of the desalination unit are described as; annual fixed Cost (AFC), sinking fund factor (SFF), salvage cost (S), annual salvage cost (ASC), Annual maintenance cost (AMC), Total annual Cost (TAC) and Cost per liter (CPL) and Md is the annual average productivity.

$$AFC = (CRP)P \tag{7}$$

$$SFF = \frac{i}{(i+1)^n - 1} \tag{8}$$

$$S = 0.2P \tag{9}$$

$$ASC = (SFF)S \tag{10}$$

$$AMC = 0.1\ AFC \tag{11}$$

$$TAC = AFC - ASC + AMC \tag{12}$$

$$CPL = \frac{TAC}{M_d} \tag{13}$$

3. Results and discussion

3.1 Solar radiation intensity

Solar radiation intensity data were recorded every week with a Mechanical Pyranometer during the consecutive months of the year. Mean solar radiation intensity data were calculated during the daytime from 07:00 AM to 04:00 PM, as showed in **Figure 5**.

The graph line shows the highest mean value of solar radiation intensity recorded up to 625.5 kJ.m-2.hr-1 at 01:00 PM. The data trend shows that solar radiation intensity starts gradually increasing from the daytime 07:00 AM to

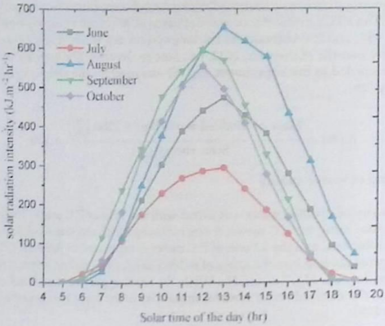

Figure 5.
Mean solar radiation intensity for the consecutive months of the year, 2012.

01:00 PM and then started gradually decreasing from 01:00 PM to 04:00 PM during he experiment. The results agree with the finding of [30, 31], who reported the ılar radiation intensity was in the range of 500 W-m-2 using the solar water esalination system with different plates. The data show that the highest solar ıdiation intensity was noted at 01:00 PM due to higher radiation. Because in the norning, the sun was clear, and radiation was highest; after the daytime 02:00 PM, the sun was covered with the light clouds, so that's why the radiation was decreasing. The results agree with the finding of [32], who reported that the solar radiation intensity was 368.00 kJ.m-2.hr-1 during October 2012. The results are in agreement with the finding of [33], who reported that the solar radiation intensity was 368.00 kJ.m-2.hr-1 during October 2010, because in the morning time radiation was least due to light clouds and air blowing in October, while the daytime from 10:00 AM the radiation was increased with the clear sky.

3.2 The temperature of the parabolic trough collector

The mean range of absorber temperature of the PTC during the time of the day, i.e., 07:00 AM to 04:00 PM, was recorded from the consecutive months of the year at different adjusting Angles, i.e., 25o, 35o, 45o, and 55o are presented in **Table 1**.

The mean highest value of absorber temperature was recorded 123oC at adjusting Angles of 45o, similar to the finding results [4], who reported the air stream temperature 120oC. Because in the morning, the sun was not clear, so the temperature was the lowest while after the daytime at 10:00 AM, the temperature was increasing with the increasing solar radiation. The data results indicated that the mean highest absorber temperature was recorded 113oC at the adjusting Angles of 25o and 35o. The results agree with the finding by [34], who reported that the absorber temperature of the PTC for the time of the day, i.e., 07:00 AM to 04:00 PM, was 18oC to 110oC during September 2011. Results are similar to the finding by [35], who reported the air stream temperature in the range of 80oC to 120oC. Similarly, the results contradict the finding of (HP 1985). It was reported

Adjusting angles	Mean ambient temperature	Mean absorber temperature
25o	25	120
35o	28	115
45o	22	123
55o	20	110

Table 1.
Adjusting angles wise range of mean temperature on PTC.

that the absorber temperature of parabolic trough solar collectors for the whole day was 69oC to 91oC in October 2011.

3.3 Performance of parabolic trough collector

The mean highest output of distilled water was ranged from 472 ml.m-2.day-1 to 782 ml.m-2.day-1 for the different adjusting Angles are shown in **Figure 6**. The mean maximum output of distilled water was recorded 782 ml.m-2.day-1 for the adjusting angles of 45o, followed by 734 ml.m-2.day-1 and 718 ml.m-2.day-1 with the adjusting angles of 35o and 25o respectively. Similarly, the mean minimum output of PTC's distilled water was noted 472 ml.m-2.day-1 with the adjusting angle of 55o because the sun path was at the range of 80o to 85o adjusting Angles for the PTC, and we collect the date up to 17 days. Results are similar to the finding [36, 37], who observed that the distilled water production increased up to 600 ml. m-2.day-1 with the solar chimney power generation-sea water desalination of the synthetic system. The results contradict the result [21, 38], who observed that the average yield of distilled water was 2300 ml. m-2.day-1 in winter on the single solar wick type distillation plant.

Figure 6 shows that the average aggregate distillation yield of solar distillation units corresponds to the average annual condition. Based on meteorological data (solar radiation) obtained from the website's information, it is assumed that the

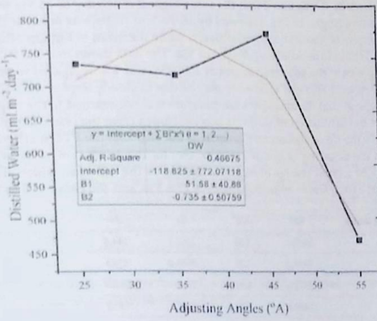

Figure 6.
Mean output of distilled water for the months of the year.

average annual condition is equal to the average condition attained during the study [50, 51]. From the results of the study, 625.5 kJ.m-2.hr-1 has been noted as the average daily solar radiation. The 550.2 kJ.m-2.hr-1 has been noted as the average yearly solar radiation in the area (as described on the website). It is reasonable to consider the test period equivalent to the average annual condition since the average annual obtainability of solar radiation in the area is appropriate to be adjacent to the experiment.

Likewise, the results are not in line with [39], who reported that water production was 6000 ml.day-1 with desalination process low temperature. The standard error bars are applied to distilled water data in the graph, which showed the standard error between the consecutive months of the year and adjusting Angles. The results are similar to the finding [40], who observed that the distilled water production increased up to 600 ml. m-2.day-1 with the solar chimney power generation-sea water desalination of the synthetic system. Results are not in line with the result [41], who reported that water production was 6000 ml. day-1 with desalination process low temperature. The results are similar to the founding of [42, 43], who observed that the distilled water production increased up to 600 ml. m-2.day-1 with the solar chimney power generation-sea water desalination of the synthetic system. However, the results are not similar to the result [18], who observed that the average yield of distilled water was 2300 ml. m-2.day-1 in winter on the single solar wick type distillation plant. Likewise, the results are not in line with the result (WD & Tamme, 2008), who reported that water production was 600 ml.day-1 with a low-temperature desalination process. PTC assisted for solar distilled water at tilt adjusting Angles of 35o and 45o worked efficiently for the maximum output of distilled water for the three consecutive months of the year.

4 The efficiency of parabolic trough collector

The efficiency of PTC at different adjusting Angles 25o, 35o, 45oand 55o during the consecutive months of the year are shown in **Table 2**. PTC's mean efficiency per day at different adjusting angles varied from 17.9% to 26.9% in **Table 2**.

From the data, it was noted that the mean highest efficiency of 26.9% was found at the adjusting Angles of 25o, followed by 26.3% and 26.1% was noted at the adjusting angles of 45o and 35o respectively, while the mean minimum efficiency was noted 17.9% at the adjusting Angles of 55o. The data shows that the PTC was performing well at the adjusting angles of 25o, 35o, and 45o compared to other adjusting Angles. PTC's low efficiency may be due to cloudy days at the adjusting Angles of 65o so that the absorber's temperature was not reached to the required amount for the distillation of water. It was concluded from the result of the mean efficiency of the three consecutive months of the year that the PTC is efficiently working at the adjusting angles of 25o, 35o, 45o, for the distillation of water. The reason may be a rapid change of sun rays striking on the collector, which affected the absorber's focal line at adjusting angles of 25o, 35o, and 45o compared to 15o, 55o

Adjusting angles	SRI	AT'	Ei	Dw	Eo	%η
25o	1480.1	1.39	2057.3	244.6	552.7	26.9
35o	1489.2	1.39	2070.0	239.1	540.3	26.1
45o	1612.6	1.39	2241.6	260.6	588.9	26.3
55o	1429.4	1.39	1986.9	157.2	355.2	17.9

Table 2.
Mean efficiency of PTC assisted for solar distilled water.

65o, respectively. Results are near the findings by [18], who reported that solar efficiency still was 16.1%. Likewise, results are similar to the finding [44]. They reported that the efficiency increases by 9.2%, with the increasing absorber area from 0.51 m2 to 0.62 m2.

3.5 Description of water quality analysis

The water twisted by the parabolic slot solar collector is estimated for quality from numerous characteristic points of view. The water management laboratory department at Peshawar Agricultural University in Pakistan verified feed water and distillate samples from various angles, i.e., 25o, 35o, 45o, and 55o. The samples were verified for pH, electrical conductivity, Alkalinity, total dissolved solids (TDS), and chloride content. **Table 3** reports the characteristic seats and average values of the three random samples composed of feed water and distillate samples from different days. The table also includes acceptable limits for available properties from the studies reported [45]. pH represents the acidity of the water sample, determined at a gauge of 0 to 14. A sample with a pH of 7.0 designate neutral values, slower than 7.0 designates acidity, and above 7.0 is considered to be essential solutions. The study results noted the range from 7.26 and 8.18 pH values of feed water samples, while for distilled water, the pH was noted with an average of 7.46.

Conductivity (E.C) (m/s) is the capability of an ingredient to conduct current, which is proportional to the absorption of numerous melted salts (obtainable in the form of ions (cations and anions)). The average value of 901.20 m/s was noted for the inlet's electrical conductivity from the study result simple. It was found that the conductivity of the distilled sample was very little up to 19.75 and 28.52 m/s associated with the inlet. Similarly, Alkalinity (mg/L) is the capability of water to counteract acids. From the present results of the study, the alkalinity value of feed water samples was detected in 400 to 412 mg/L, while 14 to 24 mg/L values were recorded for the distilled water samples. As a result, significant differences in the Alkalinity of feed water (406 mg/L) and distilled water (18.80 mg/L) samples were detected.

Total Dissolved Solids (TDS) (mg/L) assessments are indicators for assessing the overall quality of water. Therefore, the TDS test provides a qualitative measure, although it does not approximate approximates in the sample. It was detected that in feed water samples, TDS values recorded between 463 mg/L and 470 mg/L and 2.69 mg/L to 13.88 mg/L was noted for the TDS of distillate samples, which demonstrating enhancements in water quality achieved from solar energy. Similarly, the concentration of chloride in water raises electrical conductivity and, consequently, its corrosive character. The present results of the study indicated that the range of saline water was 55.00–71.90 mg/L, while for the distillate sample, the value was noted in the range of 10.90–13.40 mg/L. Therefore, it can be inferred that the quality of water obtained from solar energy is still suggestively better-quality; in addition to the above products, the production of distilled water tasteless, tasteless, and colorless. Thus, distilled water produced from parabolic trough solar collector is potable. The results agree with the finding [46, 47]; they reported that the adjusting Angles of 35o and 45o is the best for the PTC for producing maximum distilled water. The performance of PTC was best at the adjusting Angles of 35o for the maximum output of distilled water reported by [48].

3.6 Comparison of D. W regarding e. C with available distilled water IN the agriculture university Peshawar (AUP)

Distilled water obtained from PTC in the Department of Agricultural Mechanization was compared with the other distilled water, prepared with the EDU in

Property	Feedwater				Distillate water					Acceptable limit [45]
	Sample 1	Sample 2	Sample 3	Average	25o	35 o	45 o	55 o	Average	
pH	7.61	7.34	8.18	7.70	7.40	7.41	7.50	7.45	7.44	6.5–8.5
E. C (m/s)	901.00	910.00	896.00	893.33	20.12	24.40	25.80	25.10	23.85	NA
Alkalinity (mg/L)	410.00	400.00	412.00	407.33	24.00	20.00	16.00	14.00	18.5	200
TDS (mg/L)	466.00	470.00	463.00	466.33	9.55	11.49	2.69	11.58	8.82	500
Chloride (mg/L)	57.40	71.90	57.40	62.23	12.40	10.90	11.40	11.90	11.65	250

Table 3.
Properties of feed water and distilled water angle wise

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different Departments of the University regarding E.C is shown in **Figure 7**. The E.C of distilled water which was prepared in the Department of Agricultural Mechanization through PTC was 18μS.cm-1, which is in the range of the E.C of distilled water 15μS cm-1, 16μS cm-1, 19μS cm-1, and 20μS cm-1, which was collected from different departments of the University (AUP) which they prepared through EDU. From the E.C meter of the distilled water, it is clear from **Figure 7** that the E.C of distilled water prepared by PTC is similar to the prepared distilled water through EDU. Standard error bars are applied to the E.C data of distilled water of different department wise, which showed how much error is present in the data. For Peshawar-Pakistan climatic conditions, the annual average daily yield from the parabolic trough solar distillation unit can be assumed to be 782 ml.m-2.day-1 [49].

Nevertheless, the economic assistances analysis described below will highlight the effects of design parameters, i.e., adjusting parabolic trough solar distillation unit angles. The solar distillation unit is expected to function for an ordinary of 153 days per year (established on the yearly sunshine period in North Peshawar-Pakistan). **Table 4** encapsulates the outcomes of the economic investigation.

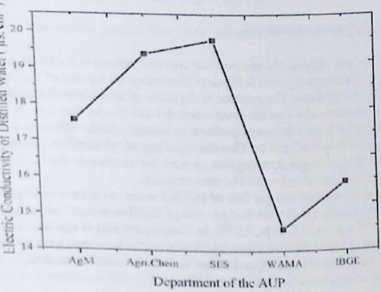

Figure 7.
Electric conductivity of distilled water in departments of the university.

Economic parameters	Value
Fixed Cost	Rs, 10,000
Annual salvage cost	Rs, 110 per annum
Annual fixed cost	Rs, 2000 per annum
Annual maintenance cost	Rs, 200 per annum
Annual water productivity	281.520 L.m-2
The market price of distilled water	Rs, 13/L
Total annual cost	Rs, 1800/annum
Cost of water produced	Rs, 2.64/L-day
Payback period	365 days

Table 4.
Economic analysis of solar distillation unit.

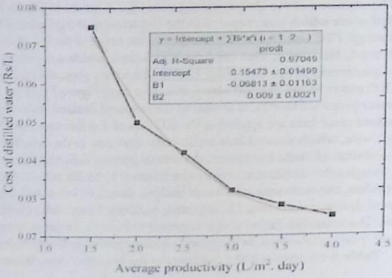

Figure 8.
Cost of average productivity of distilled water.

Based on cost analysis, the assessed unit cost of fractions is Rs 2.64/L2. Correspondingly, the payback period is 365 days (Because a sunny day of the year is supposed to be 153 days). The decrease in the angle of alteration of the solar distillation device has little effect on the desalination device's production rate. Nevertheless, in this study, the angle adjustment has been an essential factor affecting solar distillation devices' daily productivity. Therefore, the impact of distillate production on water costs was investigated, taking into account the increase in distillate production in the four cases considered under the present study.

Assess the consistent rate per liter of distilled water, as shown in **Figure** 8. The study results concluded that the cost per unit of distillation had been suggestively decreased from Rs, 4.92/L to Rs, 1.57/L. As a result, the cost is significantly reduced (approximately 68%) distilled water achieved with the increase in distillation components, resulting from improvements in the solar distillation design, with adjustment angles, i.e., 25o, 35o, 45o, and 55o.

4. Conclusion

Water and energy are the basic needs for us to lead an everyday life on Earth. Solar energy technologies and their usage are the most important and useful for developing countries to sustain their energy needs. For the distillation process, the use of solar energy is one of the essential techniques. From the results of the laboratory experiment, it was concluded that:

- A PTC can be used for the production of a reasonable amount of distilled water.
- For the maximum amount of distilled water for PTC, the adjusting angels were recommended 25o, 35o, and 45o.
- From the results, it was cleared that PTC's maximum efficiency was noted 26.9%, 26.3%, and 26.1% for the adjusting Angles 25o, 45o, and 35o, respectively.
- The cost per distiller has been expressively compact from Rs 4.92/L to Rs 1.57/L.

- The average unit price of solar distillate is still evaluated at Rs 2.64/L-m2, with a recovery period of 365 days.

After careful considering of the experiment, the following suggestion drawn from the results of the study:

- The PTC is a cheap source of making solar distilled water as compared to the EDU plant.
- The collector should be placed in open space for absorbing maximum solar radiation to get maximum distillation.
- The collector's focal point should be re-adjustable, and the reflecting sheet should be used as good quality.
- For increasing collector efficiency, a sensor revolving system should be developed concerning direct reflection of sun rays.
- To repeat the experiment for the whole year at different adjusting Angles and day timings.

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Declarations

Availability of data and materials: The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests: The authors declare that they have no competing inter ests" in this section.

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Author Contributions: The research article with several authors has its contr butions to work. Fahim Ullah conducted the experimental work, methodology, formal analysis, and data curation, writing-original draft preparation. At the same time, Mansoor Khan Khattak reviewed and editing as well as supervised.

Nomenclature

Y (cm)	Depth of Parabola
X (cm)	Diameter of Parabola
f (cm)	The focal point of Parabola
Art (cm2)	The cross-sectional area of Parabolic Trough
Wrt (cm)	Width of parabolic trough
Lrt (cm)	Length of parabolic trough
Aab (cm2)	The cross-sectional area of the Absorber pipe
π (3.14)	Constant term

Dab (cm)	The diameter of the Absorber pipe
Lab (cm)	Length of Absorber pipe
Is (SRI)	Solar Radiation Intensity (kJ.m-2.hr-1)
Vc	Mechanical Pyranograph value (Cal.m-2.sec-1)
η	Efficiency
2260	Vaporization requirement (kJ-kg-1)
AT	Area of Parabolic Trough (m2)
Ei	Energy Input (kJ.m-2.hr-1)
DW	Distilled water (m.hr-1)
Eo	Energy output (kJ.m-2.hr-1)
Vab	The volume of the Absorber pipe (cm3)
R	The radius of the Absorber pipe

Acronyms

PTC	Parabolic Trough Collector
SDW	Solar Distilled Water
E.C	Electrical Conductivity
S.I	System International Unit
KCL	Potassium Chloride Solution
Ca, Mg, Zn, and Na	Calcium, Magnesium, Zinc, and Sodium
EDM	Electrical Conductivity Meter

Author details

Fahim Ullah[1,2]*

1 Joint International Research Laboratory of Information Display and Visualization, School of Electronic Science and Engineering, Southeast University, Nanjing, P.R. China

2 Department of Agricultural Mechanization, FCPS, The University of Agriculture, Peshawar, KP, Pakistan

*Address all correspondence to: fahimullah320@seu.edu.cn

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Section 4

Computer Applications in Agriculture

Chapter 22

Precision in Agriculture Decision Making Based on Machine Learning

Ratnmala Bhimanpallewar and M.R. Narasinga Rao

Abstract

Farming is the one of the major occupations in India. Increase in population is increasing the demand of food, whereas soil degradation causing decrease in yield. Technology is contributing in agriculture domain through software and hardware enhancement. One of the software-based contribution is for predicting the suitable crop. Same field can be suitable for one crop and not for another one, so it is better to choose the one which can lead to better yield. There are many predictive algorithms available. Algorithms which can work for suitability analysis need to test and choose the best one. Such predictive algorithms need dataset in appropriate format. Once the quality data is available correct predictions can be made. Data mining, machine learning are the branches comprise of algorithms, which can be trained based on dataset. Here we are introducing algorithms for decision making based on field data.

Keywords: machine-learning, agriculture, suitability, yield, dataset, algorithm, fragmented land, crop

1. Introduction

Agriculture is the main occupation in India and no doubt experienced farmers are the expert at doing everything. They can take the decisions; some decisions may fail so need to do some analysis for good results. One of the decisions we are considering here is "which crop to be adopted to have better yield?". It needs to analyze all the features on which yield is dependent and predict the suitable crop/crops. The basic feature i.e. agriculture land is the natural feature, which cannot prepare artificially and that too increase in the soil degradation is one of the serious issues farmers are facing [1]. There are multiple reasons affecting on soil quality one of them is, use of fertilizers without knowledge. For increasing yield farmers are using unbalanced quantity of fertilizers [2], without knowing the effect of it.

Even young farmers cannot take decision about which crop is suitable for current situation (soil quality, environment etc.). Farmers are adopting some crop and using chemicals for better yield, we have a good example for this from case study at Kolhapur district [3] which was resulted in causing cancer. To avoid such worst impacts we are thinking about recommending the suitable crop/crops. To get the genuine decision we are using historical data. Once the pattern of historical results identified successfully, predictions can be done appropriately.

There are many algorithmic approaches available for predictive analysis, machine learning is the branch which makes computer to learn from the dataset available. We are discussing about the 1) Role of machine learning in precise decision making about agriculture, 2) How to classify suitability level of crop/crops and feature values.

2. Agriculture decision making: Current scenario

Since old days farmers are taking farming decisions about agriculture by experience. Here we are discussing about the decision of choosing the crop to be adopted. Though agriculture is a major sector in India, same trend is going on. Automated and advanced systems in the form of software and physical machines are invented and available for use in developed countries, some of them are available in developing countries like India as well. Available facilities are either unaffordable or not easily approachable. Some systems are developed for some particular geographical area, it cannot be adopted for India as it is. Software techniques available in developed countries are not applicable due to fragmented land, because those systems are developed considering unfragmented land.

In India Krishi Vigyan Kendra (KVK) are the centers made available for farmer's guidance. It is responsible to spread technical knowledge among farmers. They conduct training, awareness programs to achieve some goals set as below:

1. Develop advisory services for farmers.

2. Conduct training program on different trends.

3. Conduct training programs for different level of people working in agriculture.

4. Agriculture field testing

5. Demonstration for recent innovations

It is playing an important role for needy farmers. Multiple KVK centers are there, so they can work according to the location to develop location specific solutions. It also has contribution in providing quality products like planting material, seed, organic material, livestock related products etc. As above mentioned, all agriculture related centers are available to facilitate people working in agriculture sector.

Despite all the knowledge centers, testing facilities available, farmers are continuing with traditional methods. The major change they have adopted is after Green revolution. Green revolution has shown drastic increase on yield [4, 5]. Other than using high-yielding varieties of seeds and the improved quality of fertilizers farmers are not interested to adopt new technics. There are many reasons behind it, as discussed further.

The one who work in farm are not well educated, not aware about the ongoing innovations. Even if they become aware, they cannot afford it. Economic condition of most of the farmers in India is not sufficient to purchase the automated systems available in the market. At another end, the educated, economically well, and aware people not much involved in actual farming and related occupations. The traditional farming methods are dependent on natural parameters. Uncertainty in the nature directly effects on agriculture production, so not getting yield as expected.

Thus, since long ago there is no improvement in the economic condition of small/marginal scale farmers in India.

3. Existing systems

Decision making system available in other countries. One of the popular decision making system is Agriculture Land Suitability Evaluator (ALSE), is the crop specific evaluator at Peninsular Malaysia [6]. Here crop specific means, it works for mango, citrus, guava, papaya and banana as well. Base for decision making is cultivation history, cultivation knowledge, land characteristics, climate features such as annual precipitation, dry season length per month, land slope, nutrient availability, and retention. Some other features are used for land availability and suitability evaluation in Tuban Regency, Java Island [7]. Spatial multi-criteria analysis has been done based on parameters like, land elevation, slope, slope direction, land use/land cover, land capability, integrating soil order, climate, and accessibility. Outcome prepared was land use plan by the spatial pattern. This is the area having most fertile land in the country. The weights are assigned to above mentioned criteria with the help of eight experts involved for sub-criterions. Criteria wise scores are assigned in the range of 0–10, according to involvement of sub criterions under each criterion. Weighted sum overlay method used those weights to prepare suitability map. Suitability analysis for crop Soybean in Indonesia [8], to satisfy the local need. Regular domestic consumption of soybean was more so the, need were not fulfilled. The research was conducted in Karawang Regency, West Java, Indonesia to identify suitable area for soyabean plantations in paddy fields and prepared plan for it. The suitability classes defined according to FAO categories from suitable (S2) to not suitable (N). For wheat crop suitability analysis conducted in North Carolina [9]. The case study under taken was rain-fed wheat. Five criterions considered were soil-fertility, climate, soil-features, soil-organic-matter, soil-quality, soil-chemistry and seventeen sub-criteria under that. This system also considers geographic information systems (GIS) as base and the square root method is used, called multi-criteria analysis. Percentage of land suitability for organic wheat was highly suitable- 18.6% and moderately suitable- 76.8% in Duplin country. Existing yield simulation method was also based on Moderate Resolution Imaging Spectroradiometer [10]. A case study for corn and soybean yield simulated within a certain scope of area, predictions are given by the United States Department of Agriculture (USAD)- National Agricultural Statistics Service (NASS). All above discussed systems are suitable for unfragmented land not for fragmented lands I India.

Decision making system available in India

As discussed above still the decision making in India mainly for small/marginal scale fields is by traditional way. So, farmers are not getting expected yield due to many reasons like decreasing quality of soil, uncertainty in nature. Till the moment automated machines are not used by small/marginal scale Indian farmers and are dependent on labors. There are many reasons which makes them to be dependent on labors as below:

1. Poor economic condition, so unable to purchase machines.
2. In fragmented lands, it is difficult to use the big machineries like tractor and tractor accessories.

3. Unaffordable cost of automated systems.

4. Unaware due to lack of interest.

Though the farming is the main occupation in India, due to urbanization people are moving to urban areas in search of jobs and it causes labor deficiency. So, labor cost is increasing which add on to farming expenses and again it is lowers the economic condition of farmers.

4. Introduction to technology in agriculture decision making

Decision making is in the context of choosing the appropriate crop which give good outcome in available natural conditions like soil, environment. The reason behind it is soil and environment cannot be controlled. So, first we need to study about the technologies available to analyze the data collected through monitoring and recording the soil and environmental features. There are existing prediction techniques we can study to choose the suitable method and we can do the crop suitability analysis based on historical data. Suitability analysis will give the level of suitability for crop/crops and then user can take the decision accordingly. The crop/crops having fair suitability level can be adopted for better yield.

We have divided this advisory system into sub parts as below:

4.1 Collecting data

4.1.1 Identifying the features

The first important task is to identify the features affecting on crop yield. As per the guidelines available at country level [11], state-wise [12], local [13] through variety of sources. We have listed the fallowing recurrent features from variety of sources and suitable ranges of the possible features.

a. Topography

b. Temperature

c. Soil type

d. Soil Quality

e. Rainfall

f. Soil moisture

g. pH

h. EC

i. Soil nutrients: Nitrogen, Phosphorus, Potassium

j. Soil micronutrients

All above features and some features can be added or removed as per requirement and availability of data like humidity, soil texture etc. Some of the features remain constant for the period of a year or more than that ex. Topography of land does not change for years. Some features need to measure for the period of a season or less than that ex. rainfall required at the beginning that is seeding phase of the crop is different than the growing phase of the crop. As usual we are considering two seasons of cropping i.e. Kharif and Rabi. There are three main phases of the crop seeding, growing and maturity. Each phase has different requirement for rainfall, soil-moisture, temperature, nitrogen level, phosphorus level and potassium level. We will discuss about the influence of features on crop growth one by one. To consider these values for analysis purpose we need to normalize the feature values. Some of the feature values are considered in the numeric form and some need to convert into categorical form. Textual values cannot be considered as it is, it needs to map to the numeric categories. For better understanding of the technique let us take an example of the crop wheat.

a. Topography

Topography is nothing but the slope of the crop land. The field having slope less than 10 degree is good to use for cropping. It is a natural feature which can be controlled artificially. With or without analysis we can say this is vital feature contributing towards decision making for crop suitability. Sloppy fields are not good at holding the water at higher ends and may have clayey soil at lower end this uneven nature is not suitable for crop growth. Some of the crops with less water requirement can be adopted provided the slope is less. To use the topography values for algorithm purpose we have categorized it. Plane surface is always most suitable for every crop so, the categorization is done as 1-Plane, 2- slope less than 10 degree and 3-slope more than 10 degree.

b. Temperature

It is again a natural parameter. Geographical location of India is such that enough solar energy is available. This feature values need to consider phase wise. Suitable ranges of temperature is discussed in **Table 1**. If temperature goes below or above the range crop yield get reduced. The values of temperature can be considered as it is in the numeric form with unit °C (degree Celsius).

c. Soil type

Type of the soil plays a key role in crop yield. Water holding capacity is dependent on the soil type. For some of the crops clayey soil is good and for

Sr. No.	Temperature	Soil quality	Suitability
1	24°C	Good	LevelI
2	22°C	Good	LevelI
3	20 °C	Good	LevelI

Table 1.
Sample tuple in dataset.

some loamy. Few crops can be grown in sandy soil as well. Soil type is textual value, cannot be considered as it is. Here we are categorizing it according to water holding capacity. First category is 1- Loamy, 2- Clayey, 3- Slity, 4- Sandy.

d.Soil quality

Quality of the soil is dependent on multiple features like soil nutrients, micronutrients, texture, water holding capacity and it may varies according to the chemical used, erosion occurred etc. Krishi Vigyan Kendra helps to know the quality of soil in terms of levels. With reference to that we are considering the soil quality levels as 1- Good, 2- Moderate, 3- Marginal 4- Low.

e. Rainfall

Rainfall is the natural feature on which other features dependent. Water requirement for different crop is different. Precipitation has some annual pattern, sometimes it may vary. Here we can directly consider the numeric values or range of it for analysis purpose. This feature needs to measure according to phases of the crop.

f. Soil moisture

Water holding capacity of the soil, supplied water decides the soil moisture level. Good quality and type of soils has enough moisture content. Not only rainfall but irrigation sources also contribute to decide the soil moisture values. Here we are taking its numerical values as it is phase wise.

g. pH

It shows acidity or alkalinity of soil and is measured in pH units. Different crops can bear different level of acidity in soil and water. This numerical value is considered in the range of 0 to 14.

h.EC

Soil electrical conductivity is measure of amount of salinity, one of the indicators of soil health. Excess salinity levels occur in arid and semiarid regions. For this feature as well numeric values considered directly. The range of it is from 0.611 to 25.9 dS m − 1.

i. Soil nutrients: Nitrogen, Phosphorus, Potassium

Major soil nutrients are nitrogen, phosphorus, potassium. This feature is artificially manageable. Deficiency can be resolved by adding the fertilizers available in the market but excess amount available can not reduced in any way. If farmer get their soil tested, they come to know the existing level of nutrients and amount of fertilizers to be added. But they do not approach for it and add the fertilizers without knowing the requirement. This is leading to soil degradation. Once we know the suitable crop and existing amount of nutrients, it is easy to recommend the appropriate amount of fertilizers to add and avoid the soil degradation up to certain extent.

j. Soil micronutrients

There are subcategories of soil micronutrients. Soil cab be tested into laboratory to know the availability of micronutrients, so that we can understand one aspect of soil quality and take future decision.

These are some basic feature we have considered here. We need to keep all the information, while recording these feature values: 1) what was the location? 2) what were the date and time? 3) what was the cropping season? 4) what was the crop/crops adopted? and 5) what was the final yield? There are some other features affecting on yield but either has less effect or values are not available easily. If more factors are considered, results get quite improved.

4.1.2 Collecting data using feature values

There are two different sources from which dataset can be collected. Either we can have sensor-based device which will sense actual field features and record the dataset. According to features we want to monitor; device can be integrated with respective sensors (available in market) and microcontroller to control the data recording [14] and storing process. This method can be referred as monitoring feature values. Another method is to prepare dataset from available online or offline sources called as gathering feature values.

4.1.2.1 Monitoring feature values

Environmental data is available with the meteorological department since long ago. Parameters required for agriculture are with the different scope ex. Rainfall measured by meteorological department is area wise, city wise whereas for agriculture purpose rainfall need to measure at specific location. Soil features also vary one farm to another farm as per the crop adopted and fertilizers used. So the global reports prepared cannot be referred as it is for deciding suitable crop. Crop specific monitoring system can be used as described below to measure the field specific features.

A monitoring system with microcontroller and accessories [14] to sense the nearby features like.

a. Rainfall sensor

b. Moisture sensor

c. pH sensor

d. EC sensor

e. Environmental sensor

f. NPK measuring kit

All the accessories like above can be used to monitor the actual field. There is lot of variety in the accessories available in the market. So according to the device used, scope of monitoring that feature get varies. Depending on the area of field one or more than one system needs to plant in the same field, so that whole farm will get monitored to get more accuracy in the feature value. According to components used cost of this monitoring system get varies. The frequency of feature monitoring can be every second, minute or hour as per the code written, thus it is always editable as per user need. Data can be gathered in the tabular form, so that it can easily converted to SQL database for further analysis. Backup of data can be fetched from device as an when required. As we know microcontroller like raspberry-pi has own memory in the form SD card from which data can be fetched or we can make the provision for data transfer by using some network protocol, as raspberry-pi has default support for Wi-Fi, we just need to do the configuration and coding accordingly. This kind of data backup need only once in a season. It is better to maintain the data along with date and time (time is optional in some cases) and exact place of the data recording.

4.1.2.2 Gathering feature values

Metrological department already has the system to monitor the environmental features accurately. Also, Krishi Vigyan Kendra available at different places providing the values of soil and water features after soil and water testing. The drawback of this method is we do not get the data belongs to same location for which we want to do the suitability analysis. Metrological department has their setup at certain places only not at every place we might use for suitability analysis. KVK reports are also from the different fields, we cannot guarantee that all the soil samples collected are belongs to same location for which we want to do the suitability analysis. Here definitely we can filter out and choose the dataset belongs to same region which will give appropriate prediction. So, we collect the available and authorized data from metrology department, Krishi Vigyan Kendra and the offices working under agriculture universities and government maintaining data related to farming. This data is compiled further to fetch the values of identified features under Section 4.1.1 and crop yield value. Data need to maintain in tabular format so it can easily map to SQL database for further analysis. It is mandatory to maintain the data along with date and time (time is optional in some cases) and exact place of the data recording.

4.1.3 Preparing dataset from feature data

The frequency of monitored features can be changed by averaging the value for required interval. Same data can be customized for different purposes like weather prediction, crop suitability analysis, to understand the pattern of field features etc. Here we are talking about crop suitability analysis. Cropping seasons play important role in the crop specific suitability analysis. So, the interval for data analysis is also a season. Under season every crop goes through the three main phases seeding(s), growing(g), maturity(m). Each phase needs some basic requirement like in the seeding phase favorable temperature for wheat is 20°C -25°C, in the growing phase it is 15–30°C and in maturity phase it is 14°C -15°C [12] at state Punjab in India whereas the it can tolerate the temperature in the range of 3.5–35°C. It means if the crop gets that feature values in expected range in all the phases it will lead to better yield (i.e. high suitability level S1 or S2) otherwise yield may get reduced than expected (i.e. low suitability level S3 to N2). As per the crop season and the phase, interval of data collected is decided. Some of the features need to consider phase wise (ex. Rainfall) and for some features single value need to consider (ex. nitrogen, phosphorus, potassium (NPK). Along with the above identified features under Section 4.1.1 we also need to get to know the season, yield and crop/crops adopted for the fields considered through data gathering.

4.2 Analyze data for decision making

Collected data is further analyzed to understand the crop specific suitability for variety of crop for particular season, the one which is more suitable is advised to adopt. Here the logic is- based on historical data collected. From environmental data we understand the pattern of environmental features for current season and current phase of crop and predict that aggregate/common values in the respective season. Some of the features like NPK, pH are available as the current value of that feature, so it can be taken as it is not any prediction required here. Standard feature values/ranges required for crop is already well known to the farmers who are in farming business itself. For new farmers, the guidelines are available for cropping, feature values suitable are mentioned crop wise and phase wise under the guidelines available [12, 13]. Guidelines are available in the form of books, reports, online resources, also offline centers like KVK are always available to guide. The information provided by such resources is static information.

Here we are discussing about analyzing the suitability level of crop based on current situation dynamically. For such decision making, historical data with few current feature values can make available as discussed under Section 4.1. The suitable methodologies need to choose and customize for agriculture application. Suitability results need to compare with the existing results available, that is called as testing in machine learning. Variety of methods can be applied and then the methodology which gives more accuracy can be used further. Once the data is available, the methods based on data analysis are more suitable. Extracting the required information from available dataset is called as Data mining.

Data analysis means, identifying something based on current and historical data. Broadly it is categorized into two categories qualitative and quantitative analysis. If you want to get the answer for why, what, or how we need to go for qualitative analysis. If you want to know some statistical or categorical value, then go for quantitative analysis. Here we are discussing about suitability level analysis. According to Food and Agriculture Organization of the United Nations, suitability level is a categorical value [15], so quantitative approach has been used. Quantitative approaches further categorized as text analysis, statistical analysis, diagnostic analysis, predictive analysis, and prescriptive analysis. Here we want to predict the suitability based on historical and some current values, so need predictive analysis. If we have the historical database of the farm features along with the yield, yield of the crop/crops can decide respective suitability level of the crop for storing into dataset.

Ex. For crop C in particular farm area for season S, expected highest yield is Y_H Tones/Hector and lowest expected yield is Y_L Tones/Hector (it can be zero Tone in worst condition).

Then, interval between two adjacent levels Y_i calculated as,

$$Y_i = Y_H - Y_L / 4 \tag{1}$$

Five ranges of yield from higher to lower, are computed as,

$$\text{Level1 is} >= Y_H \tag{2}$$

$$\text{Level2 is} \left(Y_H \text{ and} \right) = Y_H - Y_i \tag{3}$$

$$\text{Level3 is} \langle \text{Level2 and} \rangle = \text{Level2} - Y_i \quad (4)$$

$$\text{Level4 is} \langle \text{Level3 and} \rangle = \text{Level3} - Y_i \quad (5)$$

$$\text{Level5 is} < \text{Level4} \quad (6)$$

Example,
Expected high yield Y_H = 20 Tones/Hector and lowest yield Y_L = 3 Tones/Hector.
So,
Interval.

$$Y_i = Y_H - Y_L / 4 = 20 - 3 = 17 / 4 = 4.25$$

$$\text{Level1 is} >= 20\,\text{Tones / Hector}$$

$$\text{Level2 is} \langle 20\,\text{and} \rangle = Y_H - Y_i = 20 - 4.25 (15.75\,\text{Tones / Hector})$$

$$\text{Level3 is} \langle 15.75\,\text{and} \rangle = 15.75 - 4.25 (11.5\,\text{Tones / Hector})$$

$$\text{Level4 is} \langle 11.5\,\text{and} \rangle = 11.5 - 4.25 (7.25\,\text{Tones / Hector})$$

$$\text{Level5 is} < 7.25\,\text{Tones / Hector}$$

There are five suitability levels defined by FAO [15] as below,
S1- suitable.
S2- moderately suitable.
S3- marginally suitable.
N1- not suitable due to physical reasons.
N2- not suitable due to economic reasons.
Now if we know actual yield Y then, suitability level decided as,

$$\text{If Yield falls under Level1 then, suitability level} -> \text{S1} \quad (7)$$

$$\text{If Yield falls under Level2 then, suitability level} -> \text{S2} \quad (8)$$

$$\text{If Yield falls under Level3 then, suitability level} -> \text{S3} \quad (9)$$

$$\text{If Yield falls under Level4 then, suitability level} -> \text{N1} \quad (10)$$

$$\text{If Yield falls under Level5 then, suitability level} -> \text{N2} \quad (11)$$

Thus, we can get the values for suitability level for historical dataset.

5. Machine learning: Methods and applications

Machine learning is the analysis technique which enables computer to learn from experience. Here experience is in the form of dataset. More the accuracy in dataset more accurate the results are. Here accuracy has the different dimensions. It depends on multiple things like 1)Duration of the dataset captured (ex. Data gathered from last 10 years is better than the data captured for last 1–2 years), 2) Features considered (It's better to consider maximum characteristics on which crop yield is dependent), 3)Frequency of the data recording (ex. The values of the features in field varies after certain time, so it's better if we could record every variation in dataset), 4)Duration of the data considered for analysis (ex. To do predictive analysis for the crop in kharif season we need to consider data recorded in kharif season only, the data recorded in rabi season will work as noise). 5)Missing data (if missing data is more in proportion then accuracy in data decreased). We can prepare the dataset from historical data available and the monitoring device. Learning from the historical data and comprehending for current situation is known as supervised machine learning, one of the best predictive analysis techniques. Supervised machine learning is further categorized into regression, classification, naive Bayesian model, random forest model, neural networks, support vector machines.

Classification is the method where we divide dataset into defined classes. Class is nothing but category of the instance. Ex. In a school student are categorized into different classes. The class is decided based on features of the student like age, result of the previous year, date of birth etc. Based on marks of the students, further they can be categorized into pass class and fail class.

6. Role of machine learning in agriculture decision making

Some of methods are already used in agriculture, those are decision making methods based on some mathematical computations. More or less those are based on basic features of machine learning. Few examples we will discuss here. A land evaluation is done based on features belong to climate and site-soil [16]. It is developed using statistics and neural network model techniques. This is bit static method not user friendly, so not used widely. Decision support system [6] is based on soil features like topography, nutrients, history of cultivation, precipitation e Static categorization of the feature values is done to evaluate suitability level. Th drawback of this system is also a static nature. Konstantinos G Liakos has discu in detail how machine learning played role in agriculture precision through cro management, yield prediction, disease detection, soil and water management [1. Patricio and Rieder [18] mentioned that artificial intelligence plays important role in improving accuracy in agriculture. During 2013–2017 data captured by camera was analyzed using support vector machine classifier. Uddin, Mohammad Shorif has discussed contribution of machine learning and computer vision in agriculture [19]. Machine learning helps in decision making, for better productivity and more precise systems. In developed countries machine learning is introduced in agriculture too early for different purpose like farming prediction is done using classification [20, 21], Artificial Neural Network technique used for crop yield prediction [22]. Even for study regarding plant disease statistical and machine learning approaches has been used [23–27].

Decision making about suitable crop

As we have discussed under Section 4, we can get the feature values for a particular crop in a particular season as per the list of features identified under Section 4.1.1 and also, we can compute the level of suitability of the same crop using the methodology discussed under Section 4.2. Here, crops specific suitability is considered as output class. Suitability level is further divided into five classes [15], so classification method of machine learning is chosen. According to the discussion under Section 5, we can say that supervised technique classification is suitable for crop specific suitability analysis. We can treat the computed suitability levels based on yield as class-value for that particular record/tuple and all other feature-values as input-feature-values of the same tuple. Any classification technique, which can classify the records into more than one classes based on input features called as multi-class classification technique. Any multi-class classification technique can be used and further customized [28] to get the appropriate suitability analysis. Similar to output classes computed using Eqs. (7)–(11) input classes can be computed as below.

If input feature is categorical value then no need to compute the levels, it can be directly mapped. Example soil quality is one of the features need to consider having three different having categorical values good, moderate and average. Then it will be mapped to input levels as below:

Level1	Soil_quality = Good
Level2	Soil_quality = Moderate
Level3	Soil_quality = Average

Let us consider the input X_i is environment feature temperature at Punjab state in India. Lowest temperature is considered as 0°C and highest temperature observed is 50°C. We know in the growing phase of the crop wheat for high growth rate the favorable temperature is 20–25°C. Wheat cannot tolerate the temperature below 3.5°C so, Level5 is less than or equal to 3.5°C. It cannot tolerate the temperature above 35°C so, Level1 is above 35°C.

Thus,
Highest value is 35°C
Lowest value is 3.5°C
So, as per Eq. (1) interval is calculated as,
$X_i = (35–3.5)/4 = 7.75$.
X_1 is 35
X_2 is $X_1 - X_i = 35–7.75 = 19.5$
X_3 is $X_2 - X_i = 27–8 = 11.75$
X_4 is $X_3 - X_i = 21–8 = 4$

To convert into input class levels, the dynamic levels will be computed. If the available dataset has tuples as shown in **Table 1**.

To simplify we will round up the values. The levels will be converted as below.

Level1 > =35°C.
Level2 < 35°C and > = 20°C.
Level3 < 20°C and > =12°C.
Level4 < 12°C and > =4°C.
Level5 < 4°C.

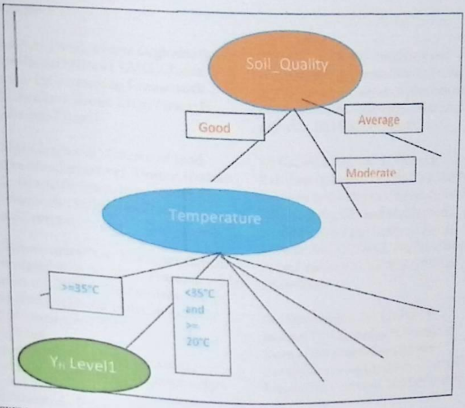

Figure 1.
Decision making tree.

Now, as per tuples in database for suitability level 1 of output the mapping input level in Level2, thus for decision tree classification intermediate result based on above data belongs **Table 1**, partial decision tree will be as shown in **Figure 1**.

Based on simple dataset available as per **Table 1**, simple decision tree has been formed. If more features will be considered levels of the tree will be increased. Always the last level of the tree will output class i.e. suitability/yield level. For n number of input features tree will have n + 1 level [29].

7. Conclusion

We can conclude that machine learning can be applied in agriculture decision making. More the balanced and appropriate dataset is available better the decision can be taken. Here the machine learning approach we used, called as decision tree classification. So, we can say quality of decision tree formation is dependent on quality of input dataset. Advanced decision tree approaches work on variety of data values like categorical, constant and discrete (numerical as well as text values with some preprocessing) values. We can consider all these variety of agriculture features for processing and decision making.

Author details

Ratnmala Bhimanpallewar[1*] and M.R. Narasinga Rao[2]

1 Vishwakarma Institute of Information Technology, Pune, India

2 K.L. University, Vijayawada, India

*Address all correspondence to: ratnmalab@gmail.com

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Chapter 23

Tomato Leaf Diseases Detection Using Deep Learning Technique

Muhammad E.H. Chowdhury, Tawsifur Rahman, Amith Khandakar, Nabil Ibtehaz, Aftab Ullah Khan, Muhammad Salman Khan, Nasser Al-Emadi, Mamun Bin Ibne Reaz, Mohammad Tariqul Islam and Sawal Hamid Md. Ali

Abstract

Plants are a major source of food for the world population. Plant diseases contribute to production loss, which can be tackled with continuous monitoring. Manual plant disease monitoring is both laborious and error-prone. Early detection of plant diseases using computer vision and artificial intelligence (AI) can help to reduce the adverse effects of diseases and also helps to overcome the shortcomings of continuous human monitoring. In this study, we have extensively studied the performance of the different state-of-the-art convolutional neural networks (CNNs) classification network architectures i.e. ResNet18, MobileNet, DenseNet201, and InceptionV3 on 18,162 plain tomato leaf images to classify tomato diseases. The comparative performance of the models for the binary classification (healthy and unhealthy leaves), six-class classification (healthy and various groups of diseased leaves), and ten-class classification (healthy and various types of unhealthy leaves) are also reported. InceptionV3 showed superior performance for the binary classification using plain leaf images with an accuracy of 99.2%. DenseNet201 also outperform for six-class classification with an accuracy of 97.99%. Finally, DenseNet201 achieved an accuracy of 98.05% for ten-class classification. It can be concluded that deep architectures performed better at classifying the diseases for the three experiments. The performance of each of the experimental studies reported in this work outperforms the existing literature.

Keywords: Smart agriculture, automatic plant disease detection, deep learning, CNN, classification

1. Introduction

Thousands of years ago, the development of agriculture led to the domestication of main food crops and animals today. One of the major global problems that humanity faces today is food insecurity [1] of which plant diseases are a major cause [2]. According to one estimate, plant diseases collectively account for a crop yield loss of around 16% globally [3]. The global potential loss from pests is estimated to be around 50% for wheat and 26–29% for soybean [3]. Plant pathogens are

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classified into major groups of fungi, fungus-like organisms, bacteria, virus, viroid, virus-like organism, nematodes, protozoa, algae, and parasitic plants. Artificial intelligence (AI), machine learning (ML), and computer vision have provided significant help in numerous applications including power prediction from renewable resources [4, 5] and biomedical applications [6, 7]. The application of AI has seen a great boost during the COVID-19 pandemic period for the detection of lung-related diseases [8–11] and other prognostic applications [12]. Similar advanced technology can be used to mitigate the adverse effects of plant diseases by their early-stage detection and diagnosis. Recently, the application of AI and computer vision to automatic detection and diagnosis of plant diseases is being extensively studied because manual plant disease monitoring is tedious, time-consuming, and labor-intensive. Sidharth et al. [13] applied a Bacterial Foraging Optimization-based Radial Basis Function Network (BRBFNN) to automatically identify and classify plant disease achieving the classification accuracy of 83.07%. Convolutional neural network (CNN) is a very popular neural network architecture that is used successfully for a variety of computer vision tasks in diverse fields [14]. CNN architecture and its different variants have been utilized by researchers for the classification and detection of plant diseases. Sunayana et al. [15] compared different CNN architectures for disease detection in potato and mango leaves achieving an accuracy of 98.33% for AlexNet and 90.85% for a shallow CNN model. Guan et al. [15, 16] used a pre-trained VGG16 model to estimate the disease severity in apple plants and achieved an accuracy of 90.40%. Jihen et al. [17] used LeNet [18] model to classify healthy and diseased banana leaves and achieved an accuracy of 99.72%.

Tomato is a major food crop across the globe with a per capita consumption of 20 kilograms per year and represents about 15% of average total vegetable consumption. North America is consuming 42 kilograms of tomatoes per capita per year while Europe is consuming 31 kilograms of tomatoes per capita per year [19, 20]. To meet the global demand for tomatoes, it is imperative to devise techniques for improving crop yield and early detection of pests, bacterial, and viral infections. Several works have been done in employing artificial intelligence-based techniques to improve tomato plants' survival by early detection of diseases and subsequent disease management. Manpreet et al. [21] used a pre-trained CNN-based architecture known as Residual Network or commonly called ResNet to classify seven tomato diseases with an accuracy of 98.8%. Rahman et al. [22] proposed a deep learning-based fully-connected network to classify Bacterial Spot, Late Blight, and Septorial Spot disease from tomato leaf images and achieved an accuracy of 99.25%. Fuentes et al. [23] to classify ten diseases from tomato leaves images considered three main families of detectors: Faster Region-based Convolutional Neural Network (Faster R-CNN), Region-based Fully Convolutional Network (R-FCN), and Single Shot Multibox Detector (SSD). These detectors were combined with different variants of deep feature extractors VGG16, ResNet50, and ResNet152 for Faster R-CNN, ResNet-50 for SSD, and ResNet-50 for R-FCN for real-time disease and pests' recognition and achieved the highest Average Precision of 83% with VGG16 on top of FRCNN. Agarwal et al. [24] proposed a Tomato Leaf Disease Detection (ToLeD) model, a CNN-based architecture for the classification of ten diseases from tomato leaves images achieving an accuracy of 91.2%. Durmuş et al. [25] evaluated AlexNet and SqueezeNet architectures for the classification of ten diseases from tomato leaves images and achieved an accuracy of 95.5%. Although the disease classification and detection in plant leaves are well-studied in tomatoes and other plants, the reliability of leaf images with varying back-ground on large image classes are not well-studied, since the real-world images can vary greatly in terms of lighting conditions, image quality, orientation, etc. [18].

This chapter has the following main contributions: (i) Investigation of the classification tasks for different variants of CNN architecture for binary and different multi-class classifications of tomato diseases. Several experiments employing different CNN architectures were conducted on raw images. Three different types of classifications were done in this work: (a) Binary classification of healthy and diseased leaves, (b) Six-class classification of healthy and four diseased leaves, and finally, (c) Ten-class classification with healthy and 9 different diseases classes. (ii) The performance achieved in this work outperforms the existing state-of-the-art works in this domain.

The rest of the chapter is organized in the following manner: Section 1 gives a brief introduction, literature review, and motivation for the study. Section 2 describes the different types of plant pathogens. Section 3 provides the methodology of the study with technical details such as the dataset description, pre-processing techniques, and details of the experiments. Section 4 reports the results of the studies followed by discussions in Section 5 and finally, the conclusion is provided in Section 6.

2. Pathogens of tomato leaves

Fungi is the predominant plant pathogens and it can cause multiple diseases including early blight, septoria leaf spot, target spot, and leaf mold. Fungi can attack plants through different sources such as infected soil and seeds. Fungal infections can spread from one plant to another through animals, humans, machinery, and soil contamination. The fungal attack vectors include plant pruning wounds, insects, leaf stomata, and others. The early blight disease of tomato plants is caused by the fungus, which affects the plant leaves. If it affects the seedlings' basal stems, adult plant's stem, and fruits, it is called collar rot, stem lesion, and fruit rot, respectively [26, 27]. Numerous methods have been devised for the control of early blight but the most effective methods are cultural control i.e. efficient soil, nutrients, and crop management to reduce infections and also with the use of fungicidal chemicals. Septoria leaf spot of tomato plants is caused by fungus [28, 29], which releases tomatinase enzyme that speeds up the degradation of tomato steroidal glycoalkaloids α-tomatine [30, 31]. The target spot disease of tomato plants is caused by the fungus [32, 33]. Symptoms of target spot disease in tomato plants are necrotic lesions of light brown color in the center [34, 35]. The lesions spread to a larger blighted leaf area and result in early defoliation [34, 35]. The target spot also damages the fruit directly by entering into the fruit pulp [34, 35]. The leaf mold disease of plants is caused by the fungus [36, 37]. It occurs during periods of extended leaf wetness. Bacteria is also a major plant pathogen. Bacteria enter plants through wounds such as insect bites, pruning, cuts, and also through natural openings such as stomata. Plant's surrounding environmental conditions such as temperature, humidity, soil conditions, availability of nutrients, weather conditions, and airflow are important factors in determining the bacterial growth on the plant and the consequent damage. Bacterial spot is a plant disease caused by bacteria [38, 39]. Molds are also a major cause of plant diseases. Late blight disease of tomato and potato plants is caused by mold [40, 41]. The appearance of dark uneven blemishes on leaves tips and plant stems are a few of the symptoms. Tomato yellow leaf curl virus (TYLCV) is a devastating virus causing tomato disease. This virus attacks the plant through another insect. Although tomato plants are unhealthy diseased leaves and iii) ten-class classification of healthy and various diseased leaves. In study II, different types of tomato leaf diseases are classified into the group of diseases while in study III, different classes of unhealthy and healthy leaf images were classified. Similar experiments the primary hosts for the virus, this viral infection has been reported in several other plants including beans and pepper, tobacco, potatoes, and eggplants [42, 43]. In the last few decades, due to the rapid spread of the disease, the research focus has been shifted to damage control of yellow leaf curl disease [44–47]. Another viral disease that specifically affects tomato plants is caused by Tomato mosaic virus (ToMV). This virus is found worldwide and affects not only tomatoes but other plants as well. Symptoms of ToMV infection include twisting and fern-like appearance of leaves, damaged fruit with yellow patches, and necrotic blemishes [48, 49].

3. Methodology

The overall methodology of the study of the paper is summarized in **Figure 1**. This study used tomato leaf data from the plant village dataset [50, 51], where tomato leaf images are provided. As explained earlier, the paper has three different studies: (i) binary classification of healthy and unhealthy leaves; (ii) six-class classification of healthy and different disease group leaves were conducted; and (iii) ten class of healthy and several different diseased leaves were carried out. The classification is done using pre-trained networks- ResNet18, MobilenetV2, InceptionV3, and DenseNet201 that have been comparatively successful in previous publications [8, 10, 11, 52–57].

3.1 Datasets description

In this study, plant village tomato leaf images dataset was used [50, 51], where 18,162 tomato leaf images are available. All images were divided into 10 different classes, where one class is healthy and the other nine classes are unhealthy (such as- bacterial spot, early blight, leaf mold, septoria leaf spot, target spot, two-spotted spider mite, late bright mold, mosaic virus, and yellow leaf curl virus), and 9 unhealthy classes are categorized into five subgroups (namely-bacterial, viral, fungal, mold and mite disease). Some sample tomato leaf images, for healthy and different unhealthy classes from plant village dataset are shown in **Figure 2**. Moreover, a detailed description of the number of images in the dataset is also shown in **Table 1**, which is useful for classification tasks discussed in detail in the next section.

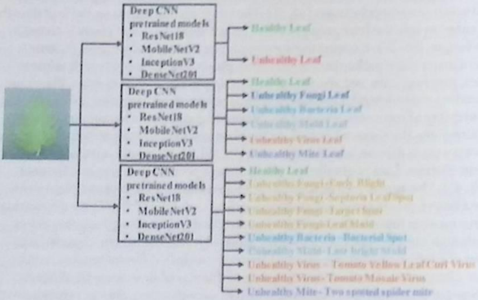

Figure 1.
Overall Methodology of the study.

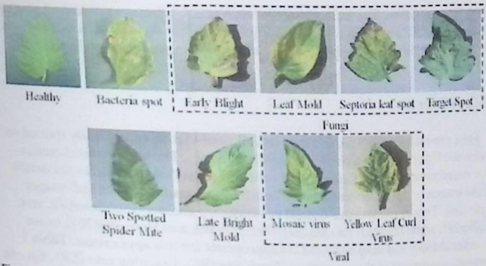

Figure 2.
Sample images of healthy and different unhealthy tomato leaves from the plant village database [3].

Class	Unhealthy					Healthy
	Fungi	Bacteria	Mold	Virus	Mite	
Sub Class	Early blight (1000)	Bacterial spot (2127)	Late bright mold (1910)	Tomato Yellow Leaf Curl Virus (5357)	Two spotted spider mite (1676)	Healthy (1591)
	Septoria leaf spot (1771)			Tomato Mosaic Virus (373)		
	Target spot (1404)					
	Leaf mold(952)					
Total Tomato Leaf Images (18,162)						

Table 1.
The number of tomato leaf images for healthy and different unhealthy classes.

3.2 Preprocessing

3.2.1 *Resizing and normalizing*

The various CNN network has input image size requirements. Thus, the images were resized to 299 × 299 for Inceptionv3 and 224 × 224 for Resnet18, MobilenetV2, and DenseNet201. Using the mean and standard deviation of the images of the dataset, z-score normalization was used to normalize the images.

3.2.2 *Augmentation*

Training with an imbalanced dataset will result in a biased model because the dataset is not balanced and does not contain a comparable number of images for the various categories. As a result, data augmentation can aid in the creation of a similar number of images in each class, resulting in reliable results, as reported in numerous recent publications [6–11]. To align the training images, three augmentation techniques (rotation, scaling, and translation) were used. The images were rotated in a clockwise and counterclockwise direction with an angle of 5 to 15 degrees for image augmentation. The scaling process involves enlarging or shrinking the image's frame size, and 2.5 percent to 10% image magnifications were used in this analysis. Image translation was accomplished by converting images by 5–20% horizontally and vertically.

3.3 Experiments

Four pre-trained CNN models were investigated that were originally trained on ImageNet Database [58] to classify tomato leaf images. Three different classification experiments were carried out in this study. **Tables 2–4** summarize the details of the images in the experiments for three different classification of leaf images separately. Two of the four pre-trained networks are shallow (MobilenetV2, and ResNet18), while the other two are deep (Inceptionv3, and DenseNet201) to see whether shallow and deep networks are appropriate for this application. **Table 5** presents a summary of the parameters (Batch size (BS), Learning rate (LR), Epochs (E), Epochs patience (EP), Loss function (LF), Optimizer (OP)) for classification in experiments.

All of the studies were conducted on an Intel Xeon Processor E5-2697 v4, 2.3 GHz with sixty-four GB RAM and a sixteen GB NVIDIA GeForce GTX 1080 GPU using the PyTorch library and Python 3.7.

Database	Types	Total No. of images/ class	For Both Segmented and Unsegmented experiment		
			Train set count/fold	Validation set count/ fold	Test set count/ fold
Plant village dataset	Healthy	1591	1147*10 = 11470	127	317
	Unhealthy (9 diseases)	16570	11930	1326	3314

Table 2.
Summary of the binary classification experiment.

Database	Types	Count of images/class	For Both Segmented and Unsegmented experiment		
			Train set count/ fold	Validation set count/fold	Test set count/fold
Plant village dataset	Healthy	1591	1147*3 = 3441	177	317
	Fungi	5127	3692	410	1025
	Bacteria	2127	1532*2 = 3064	170	425
	Mold	1910	1375*3 = 4125	153	382
	Virus	5730	4126	458	1146
	Mite	1676	1207*3 = 3621	134	335

Table 3.
Summary of the six-class classification experiment.

3.4 Performance matrix

Important performance metrics for classification experiment is stated in Eqs. (1)–(5):

$$Accuracy = \frac{TP + TN}{(TP + FN) + (FP + TN)} \tag{1}$$

$$Sensitivity = \frac{(TP)}{(TP + FN)} \tag{2}$$

$$Specificity = \frac{(TN)}{(TN + FP)} \tag{3}$$

$$Precision = \frac{(TP)}{(TP + FP)} \tag{4}$$

Database	Types	Count of images/class	For Both Segmented and Unsegmented experiment		
			Train set count/ fold	Validation set count/ fold	Test set count/ fold
Plant village dataset	Healthy	1591	1147*3 = 3441	127	317
	Early blight	1000	720*5 = 3600	80	200
	Septoria leaf spot	1771	1275*3 = 3825	142	354
	Target spot	1404	1011*3 = 3033	112	281
	Leaf mold	952	686*5 = 3430	76	190
	Bacterial spot	2127	1532*2 = 3064	170	425
	Late bright mold	1910	1375*3 = 4125	153	382
	Tomato Yellow Leaf Curl Virus	5357	3857	429	1071
	Tomato Mosaic Virus	373	268*13 = 3484	30	75

Table 4.
Summary of the ten-class classification problem.

Parameters for classification model	
BS	16
LR	0.001
E	15
EP	6
SC	5
LF	BCE
OP	ADAM

Table 5.
Summary of parameters for classification experiments.

$$F1\_score = \frac{(2 * TP)}{(2 * TP + FN + FP)} \quad (5)$$

Here, true positive (TP) is the number of correctly classified healthy leaf images and true negative (TN) is the number of correctly classified unhealthy leaf images. False-positive (FP) and false-negative (FN) are the misclassified healthy and unhealthy leaf images, respectively.

4. Results

The performance of various networks in the different experiments is reported in this section.

In this study, three different experiments were conducted for tomato leaf images and the comparative performance for four different CNNs for the three classification schemes is shown in **Table 6**. It is apparent from **Table 6** that all the evaluated pre-trained models perform very well in classifying healthy and unhealthy tomato leaf images in two-class, six-class, and ten-class problems.

Among the networks trained with leaf images for two-class, six-class, and ten-class problems, Densenet201 outperformed other trained models except without segmented two-class and with segmented six class problems where InceptionV3 was the best-performing network. Moreover, shallow networks ResNet18, and MobilenetV2 both showed comparable performance to most of the deep networks for the classification of images.

DenseNet201 outperforms others and for six-class and ten-class problems showed accuracy, sensitivity, and specificity of 97.99%, 97.99%, 99.54% and 98.05%, 98.03%, 99.76%, respectively. On the other hand, InceptionV3 produced the best result with accuracy, sensitivity, and specificity of 99.2%, 99.2%, and 96%, respectively for the two-class problem. **Figure 3** clearly shows that the Receiver operating characteristic (ROC) curves for two-class, six-class, and ten-class

Classification	Model	Overall	Weighted			
Binary Classification		Accuracy	Precision	Sensitivity	F1-score	Specificity
	ResNet18	98.4	98.4	98.37	98.37	95.2
	MobileNet	98.42	98.42	98.38	98.33	95.45
	DenseNet201	98.9	98.85	98.66	98.76	95.56
	Inceptionv3	**99.2**	**99.23**	**99.2**	**99.25**	**96**
Six-Class Classification	ResNet18	96.86	96.84	96.84	96.84	99.18
	MobileNet	96.74	96.76	96.74	96.74	99.25
	DenseNet201	**97.99**	**97.99**	**97.99**	**97.98**	**99.54**
	Inceptionv3	97.65	97.67	97.65	97.63	99.41
Ten-Class Classification	ResNet18	96.75	96.77	96.79	96.76	99.65
	MobileNet	97.2	97.18	97.19	97.17	99.7
	DenseNet201	**98.05**	**98.03**	**98.03**	**98.03**	**99.76**
	Inceptionv3	97.35	97.34	97.35	97.34	99.69

Table 6.
Summary of the tomato leaf disease classification performance using original leaf images.

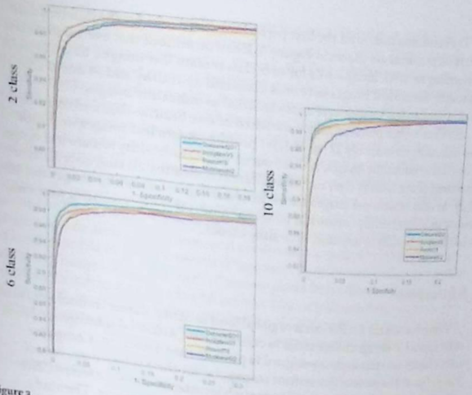

Figure 3.
Comparison of the ROC curves for healthy, and unhealthy tomato leaf image classification using CNN based models for two-class, six-class, and ten-class Classification.

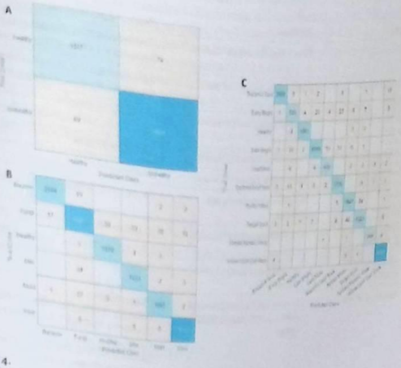

Figure 4.
Confusion Matrix for healthy, and unhealthy tomato leaf image classification using CNN based models for (A) Binary-class, (B) six-class, and (C) ten-class Classification.

problems of tomato leaf images. It is evident from **Figure 3** that network performances are comparable for 2-, 6- and 10-class problems. However, deep networks can provide better performance gain for 6- and 10-class problems.

The confusion matrix for the best performing networks for the different classification problems are shown in **Figure 4**. It can be noticed that even with the best performing network InceptionV3 for two-class tomato leaf images, 69 out of 16,570 unhealthy tomato leaf images were miss-classified as healthy and 74 out of 1,591 healthy tomato leaf images were miss-classified as unhealthy images.

For the six-class problem, which consisted of one healthy class and five different unhealthy classes, only 27 out of 1,591 healthy tomato leaf images were miss-classified as unhealthy images, and 385 out of 16,570 unhealthy tomato leaf images consisted of one healthy class and nine different unhealthy classes, only 32out of 1,591 healthy tomato leaf images were miss-classified as unhealthy images and 382 out of 16,570 unhealthy tomato leaf images of nine different categories were miss-classified as healthy or any other unhealthy classes.

5. Discussion

Plant diseases are a major threat to global food security. Latest technologies need to be applied to the agriculture sector to curb diseases. Artificial intelligence-based technologies are extensively investigated in plant disease detection. Computer vision-based disease detection systems are popular for their robustness, ease of acquiring data, and quick results. This research investigates how different CNN-based architectures perform on classification of tomato leaf images. The study was divided into 3 sub-studies of 2 class classification (Healthy, and Unhealthy), 6 class classification (Healthy, Fungi, Bacteria, Mold, Virus, and Mite), and 10 class

Paper	Database	Reported performance
P. Tm et al. [59] (2018)	Plant village dataset (10 classes)	Accuracy-94.85%, Precision-94.81%, Sensitivity-94.81%, F1 Score – 94.81%
Mohit et al. [24] (2020)	Plant village dataset (10 classes)	Accuracy-91.20%, Precision-90.90%, Sensitivity-92.90%, F1 Score-91.60%
H. Durmuş et al. [25] (2017)	Plant village dataset (10 classes)	Accuracy-95.50%
Keke et al. [60] (2018)	Plant village dataset (2 classes)	Accuracy-97.20%
Belal et al. [61] (2018)	Plant village dataset (2 classes)	Accuracy-98.00%
Ouhami et al. [62] (2020)	Own dataset (6 classes, 666 images)	Accuracy-95.65%
Fuentes et al. [63] (2018)	Plant village dataset (9 classes)	Accuracy-96.00%
Madhavi et al. [64] (2020)	Own dataset (2 classes, 520 images)	Accuracy-80.00%
Proposed Study	Plant village dataset (2 classes,6 classes, and 10 classes) 18162 images	(Binary Class) Accuracy-99.2%, Precision- 99.23%, Sensitivity-99.2%, F1 Score- 99.25% (Six Class) Accuracy-97.99%, Precision- 97.99%, Sensitivity-97.98%, F-1 Score- 97.54% and (Ten Class) Accuracy-98.05%, Precision- 98.05%, Sensitivity-98.03%, F-1 Score- 98.03%

Table 7.
Results in the paper compared with other state of the art results.

classification (Healthy, Early blight, Septoria leaf spot, Target spot, Leaf mold, Bacterial spot, Late bright mold, Tomato Yellow Leaf Curl Virus, Tomato Mosaic Virus, and Two-spotted spider mite). Overall, the DenseNet201 model outperformed every other model except for binary classification, where the InceptionV3 model outperformed other models. In the binary classification of healthy and diseased tomato leaves, InceptionV3 showed an overall accuracy of 99.2%, while DensNet201 showed an overall accuracy of 99.67%. In 6 class classification, DenseNet201 showed an overall accuracy of 97.99%, while InceptionV3 showed an overall accuracy of 97.65%. In 10 class classification, DenseNet201 showed an overall accuracy of 98.05%, while InceptionV3 showed an overall accuracy of 97.35%. The results in the paper are comparable to the state-of-the-art results and are also summarized in **Table 7**. Although the Plant Village dataset used in this study contains images taken in diverse environmental conditions, the dataset is collected in a specific region and is of specific breeds of tomatoes. A study conducted using a dataset containing images of other breeds of tomato plants from different regions of the world may result in a more robust framework for early disease detection in tomato plants. Furthermore, the lighter architecture of CNN models with non-linearity in the feature extraction layers might be useful to investigate for portable solutions.

6. Conclusion

The stages of the process into the infinite possibilities of machine learning for agriculture applications, complete with case studies. ResNet, MobileNet, DenseNet201, and InceptionV3 are examples of state-of-the-art pre-trained CNN models that do an excellent work of classifying diseases from plant leaf images. When compared to other architectures, the DenseNet201 was found to be better at extracting discriminative features from images. The trained models can be used to detect plant diseases early and automatically. As a result, preventive actions can be adopted faster. This research could help with early and automated disease detection in tomato crops, due to the use of cutting-edge technology like smartphones, drone cameras, and robotic platforms. The proposed structure can be combined with a feedback system that provides appropriate insights, treatments, disease prevention, and control techniques, resulting in improved crop yields.

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Conflict of interest

There is no conflict of interest.

Author details

Muhammad E.H. Chowdhury[1*], Tawsifur Rahman[1], Amith Khandakar[1], Nabil Ibtehaz[2], Aftab Ullah Khan[3], Muhammad Salman Khan[3,4], Nasser Al-Emadi[1], Mamun Bin Ibne Reaz[5], Mohammad Tariqul Islam[5] and Sawal Hamid Md. Ali[5]

1 Department of Electrical Engineering, Qatar University, Doha, Qatar

2 Department of Computer Science and Engineering, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh

3 AI in Healthcare, Intelligent Information Processing Laboratory, National Center for Artificial Intelligence, Pakistan

4 Department of Electrical Engineering (JC), University of Engineering and Technology, Peshawar, Pakistan

5 Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia, Bangi, Selangor, Malaysia

*Address all correspondence to: mchowdhury@qu.edu.qa

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Chapter 24

A Nonlinear Fuzzy Controller Design Using Lyapunov Functions for an Intelligent Greenhouse Management in Agriculture

Lukman Adewale Ajao, Emmanuel Adewale Adedokun, Joseph Ebosetale Okhaifoh and Habib Bello Salau

Abstract

The importance of agronomists in large-scale production of food crops under considerate environmental weather conditions cannot be overemphasized. However, emerging global warming is a threat to food security due to its effect on soil depletion and ecosystem degradation. In this work, the design of the proposed intelligent context is to observe, model and simulate greenhouse control system activity towards the management of the farm crop growth as the affected salient environmental parameters. Characteristically, temperature and humidity are the major factors that determine the crop yield in a greenhouse but the case of a dry air environment or beyond $30^{0}C - 35^{0}C$ of high air humidity will affect crop growth and productivity. A Mamdani technique of fuzzy logic controller with non-linear consequent is used for intelligent greenhouse design in the LABVIEW virtual environment. This approach is used to mimic the human thought process in the system control by setting some logical rules that guide the greenhouse functions. For the system stabilization achievement, a direct method of Lyapunov functions was proposed. The simulation model result shows that, the average temperature of $18.5^{0}C$ and humidity 65% is achieved for a decent environment of crop growth and development during winter. However, the average temperature and humidity achieved during summer is $27.5^{0}C$&70% respectively. For every season that is beyond $30.5^{0}C$ *and* 75% of temperature and humidity will require automation of roof opening and water spilled.

Keywords: Agricultural technology, Artificial intelligence, Fuzzy logic, Greenhouse, Nonlinear system

1. Introduction

Agriculture is an important aspect of any nation's development which usually requires appropriate seasoning irrigation and fertilization to produce a quantity of food products [1]. The seasoning control application of fertigation (fertilizer and irrigation) techniques has proven efficient in plant growth, development, and yield large crop production [2]. Computers and electronics play a significance role in the development and mechanization of agricultural products through the recent applications of ubiquitous technology of Internet of Things (IoT). This advancement and dynamic methods of control theories application helps improving the agricultural equipment (mechanization) and the processes. The recent integration of artificial intelligence (AI) and computational intelligence (CI) into the agro-mechanical machine and mechatronics system (embedded sensors and robotic) shaped the agricultural technology and their commercialization.

So, the studies have indicated a strong link between agriculture and economic growth as the backbone of national sources of income and commercial development [3]. The increasing demand in food consumption nationwide as resulting from increased daily population explosion that necessitated the provision of precision agriculture monitoring [4] and to ease the farming process as well as abnormalities in the farm environment. Although, farming is an essential means of increasing food production, recently its cultivation is decreasing and becoming inversely proportional to the rising population. This is partly due to the phenomenon of global warming [5]. As a result of changes in climate conditions and its threat of conservatory, the need arises for an agricultural development control system to manage this condition for high yield of crop production [6–8].

The changes in climate condition increases the tropical storm intensity and frequency due to rising temperatures and climate pattern that change mutually. Whereas, the warming of temperatures ocean and sea levels rising escalate the disaster storms growth with excess heat trapped in the atmosphere. It is observed that dissolving of heat energy and excess of carbon dioxide gas has significant damage on the ocean. Like oceanic acidification that affect reproduction and formation of animal shells, oceanic heat waves affect coral reefs with the frustration of fish migration, and oceanic dead zones created as a result of deoxygenation process [9, 10].

Consequently, there is a need to prevent and manage common emission releasing into the atmosphere with effect on agricultural crop growth and environmental degradation effect. This threat of emission releasing contributes immensely to the effect of climate change which affects the successful cultivation of farm crops [11]. The United Nations' World Meteorological Order (WMO) confirmed that the world planet is about 1.1°C warmer, and is forecasting an increase from 4–5°C towards end of the century. Others factors of agronomy-house sustenance depend on the environmental weather condition which includes temperature, humidity, winds, light intensity, and solar radiation. The statistical overview of primary sources of greenhouse gas emission is given in **Figure 1**, which include industry, transportation, building, agriculture, forestry, electricity and heat production [12]. While the sources of releasing those gases, are Methane (NH_4), Nitrous Oxide (NO), and Carbon Dioxide (CO) from the industrial processes, fossil fuel, bush burning, forestry, sewage disposal and other land use [13].

A Greenhouse is a controlled place where plants are grown under control conditions of ambient temperature, humidity, water vapor, light intensity, and carbon (iv) oxide [14]. The environmental conditions for greenhouses can be varied according to the plants need to get most out of the plants and for high efficiency. Since the environmental conditions of the greenhouse need to be adjusted for optimal growth, the size and cost of labor increase proportionally to the size of the greenhouse and the number of plants [15, 16]. A greenhouse is a structure designed with glass walls or transparent material and a glass/translucent roof used to grow food crops and plant cultivation (such as tomatoes and tropical flowers under controlled environmental conditions [17, 18].

The efficient management and monitoring of greenhouse plants condition require the integration of an artificial intelligence system (AI) or automated control system (ACS) based on context-aware software design (CASD). Therefore, a

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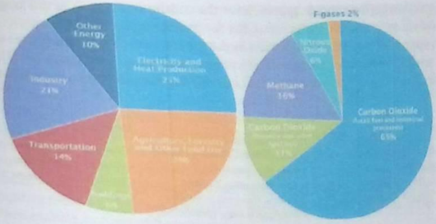

(a) (b)

Figure 1.
The statistical overview of primary sources of greenhouse gas emission. (a) The consequential effect of rapid gaseous emission (greenhouse gas emission) to the atmosphere will be increases with time. (b) This includes carbon dioxide (CO) with percentage of 147%, methane (CH_4) with percentage of 259%, and nitrous oxide (N_2O) with percentage of 132%.

Greenhouse Development Rights (GDR) framework is proposed in [19] to safeguards the right of development as a possible global solution to the climate change challenges. It is shown that GDR approach is an international context for (China and the USA) which provide funding for the development mechanism of a greenhouse as an approach to address global climate change challenges. The GDR is a foundation for future evolution and industrialized developed countries. In another approach of control and keeping hothouse cool is the development of a smart controller for grid stabilization using optoelectronic system [20].

This book chapter contribution aims at presenting an intelligent greenhouse control based on the non-linear consequent fuzzy logic controller using LabVIEW for agricultural technology. The system helps to monitoring greenhouse parameters and acts based on the specified fuzzy rules to control the system environmental condition without or with little human intervention. Thus, there is a need for an intelligent greenhouse control system in agricultural technology that can reduce human labor costs, increase productivity, and reduce human intervention.

2. Related works

The global warming crisis necessitated the development of a real-time monitoring and control system for managing change in environmental temperature conditions. This temperature change plays an important role in the soil contents of farm crops. Therefore, the use of computer technology approach (such as embedded systems and AI) has been newly adopted in realizing the design of automation control and monitoring system of ambient temperature in greenhouse management. The greenhouse control system is developed using LabVIEW simulation software for data collection and analysis of conservation in [21]. The work mainly focuses on adjusting the temperature environment using a thermostat and sensor to detect and control the hotness of the greenhouse. The process was simulated and implemented in the developing system platform of Labview software. An optimized sprinkler irrigation system for predicting use of budding land based on soil features using fuzzy logic decision approach in [22]. The significance of adopting this fuzzy logic in land evaluation is a suitable approach for the continuous nature of soil properties and provide an accurate distribution index for predicting land use.

An optimized method of cultivation in the greenhouse automated system with smart environments using an embedded system development approach in [23]. This industrial automated greenhouse model is developed for plant experimentation at

Title	Strength	Limitation
Design of an Intelligent Management System for Agricultural greenhouses based on the Internet of Things [24].	Successfully developed a remote monitoring system for greenhouses using ZigBee protocols. Users can remotely control and manage greenhouse parameters such as temperature and humidity.	Absence of an intelligent technique. Although the control method is remote, it is also manual.
Smart greenhouse monitoring using Internet of Things [25].	A system capable of remotely monitoring greenhouse parameters via a web application.	No intelligent technique presents. Lack of control mechanism.
Research on the control system of the intelligent greenhouse of IoT based on ZigBee [26].	Successfully developed a ZigBee based system capable of remotely monitoring and controlling greenhouse parameters	Absence of intelligent technique. Control is manual.
Internet of Things based smart greenhouse: remote monitoring and automatic control [27].	Implemented a smart greenhouse using GSM/GPRS for remotely monitoring and controlling greenhouse parameters. The system is capable of automatically controlling the parameters if they are out of the specified range.	Absence of an intelligent technique for the control of parameters.
Intelligent greenhouse design based on Internet of Things (IoT) [28].	Developed an intelligent greenhouse using Cloud service for remotely monitoring greenhouse variables. The system is also capable of automatically controlling the parameters if they fall below or above specified values.	Absence of intelligent control technique.
Smart greenhouse using IoT and cloud computing [16].	Successfully developed a monitoring interface for greenhouse parameters using IoT and cloud computing	Absence of intelligence and control technique.
Design and implementation of a smart greenhouse [18].	Successfully developed a smart greenhouse control system to monitor and control the parameters in a tomato farm. The system automatically controlled actuators to regulate greenhouse variables.	Absence of intelligent technique.
Intelligent Monitoring Device for Agricultural Greenhouse Using IoT [29].	The author proposes a monitoring system for greenhouses using wireless sensor networks and IoT. The proposed system incorporates a microcontroller that transmits information that can be monitored with an Android Application.	Absence of intelligent technique. No control technique specified.

Table 1.
Summary of the related works.

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the University of Alicante to control air-conditioning, soil condition, and irrigation in the system. The optimization services integrated into this system model designed help in the detection and prediction of agricultural production of smart environments. But the optimized smart environment greenhouse does not consider controlling the system conditions during rainfall, summer, and winter. Other authors that contribute to the development of automated and intelligence-based greenhouse control and monitoring system is analyzed in **Table 1**.

From these literatures, it is observed that the limitation is on the part of intelligence incorporated into the system with linearized fuzzy model improvement. Also, the season management of crop cultivated area in the greenhouse with automatic control technique are not studied. Hence, this book chapter aims to fill those gaps by implementing a non-linear consequent fuzzy logic controller system for the decision-making process and automatic control of the greenhouse system with an approach of context-aware software design ontology. This book chapter is organized into 5 sections. The introductory part discussed the general background of study in Section 1, Section 2 presented the related works. The research methodology is presented in Section 3, while sub-Section 3.1 mathematical modeling of the greenhouse control system in sub-Section 3.1, sub-Section 3.2 presented a linearize and non-linear consequent fuzzy controller design for greenhouse control. Sub-Section 3.3 contained Lyapunov function for stabilization of non-linear consequent fuzzy controller. Sub-Section 3.4 presented simulation and implementation of non-linear consequent fuzzy controller based-greenhouse design in LabVIEW. The results and discussion are presented in Section 4, sub-Section 4.1 contained Intelligent greenhouse management based nonlinear control simulation results. Sub-Section 4.2 presented simulation results of a Lyapunov stability of nonlinear control system. Section 5 gives the conclusion and recommendations for future works.

3. Methodology

Context-aware systems are software systems designed with the ability to sense (sensor) and adapt to the environmental conditions for the solution required to the problem design [30, 31] through a fuzzy controller. This design involves determining what the system needs to sense, make adaptations, and respond to sensor information. It requires sensing temperature and humidity, and then adapt to the environmental condition for the greenhouse system control and management using nonlinear fuzzy controller system with direct method of Lyapunov functions to achieved stabilization. The system modeling and design need a focus value or parameter to influence the designed value such that it can sense the elements and manipulate them in case of irregularities. So that it can make the element relevant to the purpose of the design and the designer focus. An overview of the approach

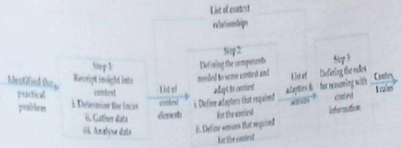

Figure 2.
An overview to the element approach in the CAS design.

design for an intelligent greenhouse control system includes practical problem identification, insight to the context, elements components required in the sense and adaptation, and logical reasoning rules for information as illustrated in **Figure 2**.

The fuzzy logic controller architecture [32] consisting of crisp input rules, Fuzzification (knowledge-based or linguistic rules), fuzzy inference engine (logic rules), and Defuzzification (output crisp values). The input of a fuzzy control system parameter can be adjusted to improve the system (fuzzy mechanism) performance using the Eqs. (1) and (2).

$$\theta^{(n)} = \alpha(P_0, P_1, P_2, P_3 \dots, P_n) \tag{1}$$

$$\theta^{(n)} = \alpha\left(\theta^{(n-1)}, P_n\right) \tag{2}$$

where, $\theta^{(n)}$ is define as a set of input parameter to adjust at time t, T_n and P_n is the parameter collected at a time T_n.

The non-homogeneity consequent of the fuzzy logic controller system technique is adopted in the design to sense the greenhouse environment and adapted for a unique solution of a design problem. A visual graphical programming system-design platform and software development environment called Laboratory Virtual Instrument Engineering Workbench (LabVIEW) was used to achieve the context-design. It is very efficient and commonly used in engineering as a context-aware system design for data acquisition, instrument control, and industrial automation system. It is a multi-threading and multiprocessing hardware system that is automatically engaged by the in-built scheduler during the execution flow structure (nodes) of a graphical block diagram. The connection wires will propagate the variables and execute the process immediately all its input data reachable.

This system is used to control the temperature and humidity of the greenhouse system using a non-homogeneity control system. The temperature and humidity inputs parameter are set and the system keeps both values constant regardless of the outside temperature of the controlled system. This is achieved using the combination technique of the linearized system with non-linear fuzzy, and adopt Lyapunov function to achieve system stability in the model. This model helps in controlling the opening greenhouse roof for rainfall and sunshine, and/or by turning on the sprinkler to reduce the temperature as presented in the algorithm of **Table 2**. The

Algorithm for greenhouse temperature management   *(Roof opening, closed and water spilled)*

t is the time, t_l is minimum air temperature, t_h is the maximum air temperature
 Procedure for greenhouse roofing control $(time, t_l, t_h)$
 $t \leftarrow$ *air temperature value*
 If time between 8 : 00*am and* 8 : 00*pm, then*
 $t_{avg} \leftarrow$ *air temperature average*
 if $t < t_l$, *then*
 Control greenhouse roofing (Closed)
 else if $t \geq t_h$
 Control greenhouse roofing (Open small)
 else
 If $t_{avg} - t < t_l$, *then*
 Control greenhouse roofing (Closed, No water spill)
 else if $t_{avg} - t \geq t_h$, *then*
 Control greenhouse roofing (Open, Water spill)

Table 2.
Greenhouse temperatures management and control

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decision-making process of the system is achieved using a combination technique of linear and non-linear approach consequent of the fuzzy logic controller system. The sub-system irrigation and ventilation classification help the agronomist to manage the setpoints of the control input variables. This irrigation-ventilation model is an intelligence unit that is used for the senses and responds to immediate action by introducing the prediction and optimization facilities that are supervised by the agronomist as presented in **Figure 3**.

The calories required for heating the air in the greenhouse is calculated as expressed in Eq. (3). For the determining value of temperature, it requires average heat of 0.30Kcal to achieve a one-meter cube of air. It is observing that 1 kW heat can produce 860Kcal, and a heat source of 30 W can produce 25.8Kcal heat per hour, and equivalent to 0.43Kcal heat per minute [33].

$$\varnothing = \mathcal{M}\mathbb{C}\Delta T \tag{3}$$

where $\varnothing$ is the heat, $\mathcal{M}$ is the mass, $\mathbb{C}$ is the heating temperature (0.24 Kcal/kg), ΔT is the difference in temperature.

3.1 Mathematical modeling of greenhouse control system

The behavior of the greenhouse microclimate is dynamic and combinations of physical processes involve mass balance and energy transfer. The physical processes involved are used in estimating the greenhouse climate. The amount of energy leaving the greenhouse can be calculated as expressed in Eqs. (4) and (5).

$$E_{total} = -E_{loss} + E_{gain} \tag{4}$$

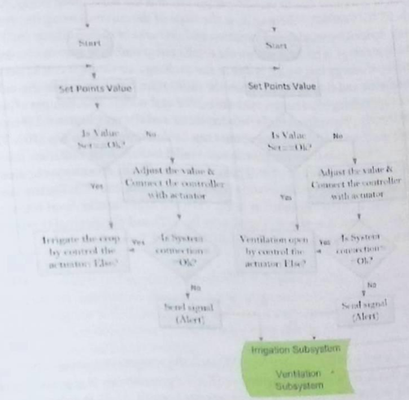

Figure 3.
Intelligent greenhouse monitoring and control flowchart.

$$E_{loss} = E_k + E_r + E_v + E_{inf} + E_{cond} \quad (5)$$

where, E_{total} is the total energy balance (W), E_{gain} is the amount of energy entering the greenhouse (W), E_{loss} is the amount of energy leaving the greenhouse (W), E_k is heat loss due to conductive heat loss (W), E_v is the heat transfer due to ventilation (W), E_{inf} is heat transfer due to infiltration (W), E_r is heat transfer due to the longwave radiation and E_{cond} is heat loss due to condensation (W).

The conductive loss encompasses all the heat transfers through the greenhouse cover from the internal to the external air, conductive heat transfer through the covering material and radiative heat transfer can be expressed as in Eq. (6). The thermal wave radiation exchange from the interior greenhouse to outside can be calculated as given in the non-linear Boltzmann relation in Eq. (7) and Eq. (8). Therefore, the ventilation of heat lost in the greenhouse is proportional to the rate of air exchange and the differences occur between the inside and outside air temperature [34], and the loss can be determined as in Eq. (9).

$$E_k = A_c h(\lambda_i - \lambda_0) \quad (6)$$

$$E_r = A_c \sigma \varepsilon (\lambda_i - \lambda_0) \quad (7)$$

$$E_v = G \rho C_p (\lambda_i - \lambda_0) \quad (8)$$

$$and, G = \omega r_v k_v A_v \quad (9)$$

where λ_o is outside air temperature (K), λ_i is inside air temperature (K), h is the conductive heat transfer coefficient (W/m^2), A is the area of greenhouse cover (m^2), Q_r is radiation loss, ε is the combining emissivity between the cover and sky, σ is Boltzmann constant, ρ is air density (kg/m^3), C is the specific heat of air (J/kg K), G is airflow due to ventilation (m^3/s), w is the wind speed (m/s), r_v is percent of the ventilator opening, k_v is the slope of the curve showing the ventilation flux divided by wind speed variation and A is area of the ventilator (m^2).

The heat energy is transfer within the intelligent greenhouse system as a result of infiltration of energy loss which is due to the exchange air through cracks occurs in the greenhouse and is considered. Since the infiltration rate is based on the volume of water vapor changed per unit cover area (roof and walls). This volume of water vapor is directly proportional to the wind velocity and the temperature difference from both inside to outside the greenhouse can be determined as in Eq. (10). Then, the sources of heat gain from the greenhouse model include solar radiation heat which is the most determinant of heat gain by the intelligent greenhouse system during crop growing and system heating from the environment [35]. So, the energy of the greenhouse can be calculated as in Eq. (11), the heat transfer from tubes to the greenhouse environment is expressed as in Eq. (12) and the internal temperature increases are within the range of (0.3–0.7) which 0.3 was chosen.

$$E_{inf} = 0.5VN(\lambda_i - \lambda_0) \quad (10)$$

$$E_r = A_g \gamma \tau I \quad (11)$$

$$Q_{hs} = mC_p(\lambda_{out} - \lambda_{in0}) \quad (12)$$

where, H_{inf} is the infiltration heat loss (W), λ_i is the temperature inside the greenhouse (K), λ_o is the outside temperature (K) of a greenhouse, V is greenhouse volume (m^3), and N is the number of air changes per hour (h^{-1}), E_r is solar energy radiate into the greenhouse environment (W), I is total external solar energy falling on a horizontal surface of the greenhouse (W/m^2), A is an area of greenhouse floor

(m^2), τ is radiation light transmission to the greenhouse cover, γ is constant of the proportion of solar radiation that radiates into the greenhouse. Q_{hs} is heat gain from the heating system (W), m is the heating water flow rate (kg/s); λ_{wi} is heating water inlet temperature (°C), λ_{wo} is heating water outlet temperature (°C) and C_p is the specific heat capacity of water (J/kg K).

3.2 A linearize and non-linear consequent fuzzy controller design for greenhouse management

A closed-loop or called feedback controller transfer function is adopted since the output of the intelligent control system $\varphi(t)$ is fed back into the system through a sensory measurement device (sensor) γ. The comparison is for reference value $\tau(t)$, where the controller system α takes the error ε (difference) between the reference point or set values and the output to adjust the inputs μ feedback to the system under control β. From the perspective of implementation of the controller with a linear approach and time-invariant, the elements of the transfer function $\alpha(s)$, $\beta(s)$, and $\gamma(s)$ do not depend on time where α is controller, β is the system under controller (plant), and sensor measurement denotes γ [36–38].

We can analyze the systems using the Laplace transform on the variables as expressed in Eqs. (13)–(16).

$$\varphi(s) = \beta(s)\mu(s) \tag{13}$$

$$\mu(s) = \alpha(s)\varepsilon(s) \tag{14}$$

$$\varepsilon(s) = \tau(s) - \gamma(s) - \varphi(s) \tag{15}$$

By solving $\varphi(s)$ in terms of $\tau(s)$ can be expressed as given in Equation

$$\varphi(s) = \left(\frac{\beta(s)\alpha(s)}{1+\beta(s)\alpha(s)\gamma(s)}\right)\tau(s) = \aleph(s)\tau(s) \tag{16}$$

The closed-loop or feedback transfer function of the greenhouse control system is expressed as $\aleph(s)$ in Eq. (17), where the numerator is identified as open-loop (forward gain) from τ input parameter to φ output values, and the denominator is a feedback loop that goes around the system called loop gain. So, if $|\beta(s)\alpha(s)| \gg 1$, that is, it has a standard model with each value of s, and if $|\gamma(s)| \approx 1$, then $\varphi(s)$ is approximately equal to $\tau(s)$ and the output system is close to the reference input.

$$\aleph(s) = \frac{\beta(s)\alpha(s)}{1+\gamma(s)\alpha(s)\alpha(s)} \tag{17}$$

The flowchart technique for a linearized and non-linear fuzzy model for the optimization function of the greenhouse control and management model is illustrated in **Figure 4**. This mechanism operates as a reference model to the non-linear system and is connected in parallel in such a way that the linear system passes across the non-linear for better stability.

The state-space model for the non-linear fuzzy controller is given in Eq. (18), which increases the fuzzy rules quantity exponentially with non-linearities measures. The delayed in the state-space model for the fuzzy controller is given in Eq. (19). Where $\dot{x}(t)$ is the state vector of $\dot{x}(t) \in \Re^{n_x}$, $\upsilon(t)$ is an input vector for $\upsilon(t) \in \Re^{n_u}$, s is the number of rules, $\omega(t)$ is the available premise vector, $\delta_k(\omega)$ is the

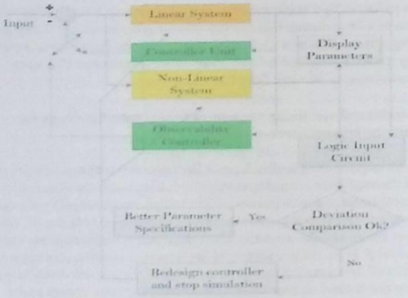

Figure 4.
Flowchart of combined linearized and non-linear fuzzy system.

membership function, α_k and β_k are the linear models, and the convex sum is given as: $\delta i(\omega) \in [0, 1], \sum_{k=1}^{l} \delta i(\omega) = 1$.

$$\dot{x}(t) = \sum_{k=1}^{l} \delta_k(\omega(t))(\alpha_k x(t) + \beta_k(t)) \tag{18}$$

This state-space model for the fuzzy system can be expanded to determined the time delay dependent as given in equation, where $\tau(t)$ is the delay time dependent, and $\delta_m(\omega(t - \tau(t)))$ is the delay states that dependent on fuzzy membership functions.

$$\dot{x}(t) = \sum_{k=1}^{l}\sum_{m=1}^{l} \delta_k(\omega(t))\delta_m(\omega(t-\tau(t)))(\alpha_{km}x(t) + \Im_{km}x(t-\tau(t)) + \beta_{km}\upsilon(t-\tau(t))) \tag{19}$$

The notation of $\tau(t) := \tau$ can be expressed as Eq. (20), and the closed-loop fuzzy model for non-linear time-dependent is in Eqs. (21) and (22). This is to reduce the number of fuzzy rules and to serve the purpose of measured-state and non-linearities unmeasured-state [34, 39, 40].

$$\Psi_{\omega\tau} = \sum_{k=1}^{l}\sum_{m=1}^{l} \delta_k(\omega(t))\delta_m(\omega(t-\tau(t)))\Psi_{km} \tag{20}$$

$$\dot{x}(t) = \alpha_{\omega\tau}x(t) + \Im_{\omega\tau}x(t-\tau) + \beta_{\omega\tau}\upsilon(t-\tau) \tag{21}$$

$$\dot{x}(t) = \alpha_{\omega\tau}x(t) + \Im_{\omega\tau}x(t-\tau) + \beta_{\omega\tau}G\psi(\xi x(t)) + \beta_{\omega\tau}\upsilon(t-\tau) \tag{22}$$

The $x(t-\tau)$ is the state vector for time-delayed, $\upsilon(t-\tau)$ is an input vector time-delayed, G is the system matrix, x(t) is a function of linear combination for each input to the model, and $\psi(\xi x(t))$ is a vector function. The boundary condition for the existence of vector function in the model can be expressed as $\psi_k, k = 1, \ldots, r$ *occur in* b_k such that; $0 \le \frac{\psi_k(v) - \psi_k(w)}{v - w} \le b_k$ as in Eq. (23).

$$\psi(!) = \begin{pmatrix} \psi_1(.) \\ \psi_2(.) \\ \psi_3(.) \\ \ldots \\ \psi_r(.) \end{pmatrix} \tag{23}$$

3.3 Lyapunov function for stabilization of non-linear consequent fuzzy controller based-greenhouse

For the stabilization and dynamical nature of the system, a Lyapunov non-linear function (LNF) is adopted to operate the system model as a linear with a limited range of function at every region. This approach of LNF helps the model to present auxiliary nonlinear feedback which can be operated as linear for control design purposes. Since a Lyapunov direct method of stability criterion for a linear system can be defined, suppose $u = 0$, and the exist two-point $p > 0$ and $q > 0$. Therefore, a linear system is asymptotically stable at the beginning for any given symmetric that existed given a unique solution that used for stability analysis as given in Eq. (24), with $\wp(\theta) = \sum_{j=1}^{m} \theta_j \wp_j$, $\wp_j > 0$, where $\eth < 0$. But the choice of q can be made arbitrarily which is mostly set as $q = 1$, an identity matrix p for all successive principal minors of p is positive using Sylvester theorem as expressed in Eq. (25).

$$\begin{aligned} \dot{x}(t) &= \alpha x(t) + \beta u(t) \\ y(t) &= \gamma x(t) + \delta u(t) \end{aligned} \tag{24}$$

$$P = \begin{matrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{matrix}, \; P_{11} > 0. \text{ Therefore } \Delta[P] > 0 \tag{25}$$

However, the parameters for the fuzzy model-dependent can be given as in Eq. (26)

$$\begin{cases} \dot{x} = \alpha(\theta)x + \beta_d(\theta)d + \beta_u(\theta)u \\ \varepsilon = \gamma_\varepsilon(\theta)x + \delta_{\varepsilon d}(\theta)d + \delta_{\varepsilon u}(\theta)u \\ y = \gamma_\varepsilon(\theta)x + \delta_{\varepsilon d}(\theta)d, \end{cases} \tag{26}$$

where $\alpha(\theta) = \sum_{i=1}^{m} \theta_i(\sigma)\alpha_i$, $\beta_d(\theta) = \sum_{i=1}^{m} \theta_i(\sigma)\beta_{d,i}$, $\beta_u(\theta) = \sum_{i=1}^{m} \theta_i(\sigma)\beta_{u,i}$, $\gamma_\varepsilon(\theta) = \sum_{i=1}^{m} \theta_i(\sigma)\gamma_{\varepsilon,i}$, $\delta_{\varepsilon d}(\theta) = \sum_{i=1}^{m} \theta_i(\sigma)\delta_{\varepsilon d,i}$, $\delta_{\varepsilon u}(\theta) = \sum_{i=1}^{m} \theta_i(\sigma)\delta_{\varepsilon u,i}$, $\gamma_y(\theta) = \sum_{i=1}^{m} \theta_i(\sigma)\gamma_{y,i}$, $\delta_{yd}(\theta) = \sum_{i=1}^{m} \theta_i(\sigma)\delta_{yd,i}$, $\theta = [\theta_1(\sigma) \ldots \theta_m(\sigma)]^T$.

The associated weighting function of normalized fuzzy with the *i*th system are calculated through the degree of fuzzy membership functions $\theta_1(\sigma)$ and premise variable with a closed interval of $[0, 1]$ which must satisfy these properties in Eq. (27);

$$0 \le \theta_i(\sigma) \le 1, \sum_{i=1}^{m} \theta_i(\sigma) = 1, \sum_{i=1}^{m} \theta_i(\sigma) = 0. \tag{27}$$

The state-space matrices function can be replaced in the derivation with a new introduce operator as expressed (Eqs. (28) and (29)), where α, P can be replaced with ω, and the subscript μ refers to all signals (x, d, ε) and η_μ is the dimension of signal μ.

$$P_\mu := \begin{bmatrix} \theta_2 I_{ne} \\ \vdots \\ \theta_m I_{ne} \end{bmatrix}, \omega^{\varsigma} := \begin{bmatrix} \omega_2 - \omega_1 \\ \vdots \\ \omega_m - I_1 \end{bmatrix}, \tag{28}$$

$$\omega^{\aleph} := [\, \omega_2 - \omega_1 \ldots \omega_m - \omega_1] \tag{29}$$

The notation in Eq. (29) can be expressed as given in Eq. (30) using fuzzy weighting membership functions properties.

$$\omega(\theta) = \sum_{i=1}^{m} \theta_i \omega_i = \omega_1 + \omega^{\aleph} P_\mu = P_\mu^T \omega^{\varsigma} \tag{30}$$

Therefore, the Lyapunov fuzzy model function for the system stability is given with $\wp(\theta) = \sum_{j=1}^{m} \theta_j \wp_j, \wp_j > 0$, where $\eth < 0$ as expressed in Eq. (31)–(33).

$$\eth = \varkappa^T \wp(\theta) \varkappa \tag{31}$$

$$\eth = \varkappa^T \left(\sum_{j=1}^{m} \theta_j \wp_j + \alpha^T(\theta) \wp(\theta) + \wp(\theta) \alpha(\theta) \right) \varkappa \tag{32}$$

$$\eth = \varkappa^T \begin{bmatrix} I_{ne} \\ \alpha(\theta) \end{bmatrix}^T \varkappa \begin{bmatrix} \sum_{j=1}^{m} \theta_j \wp_j & \wp(\theta) \\ \wp(\theta) & 0 \end{bmatrix} \begin{bmatrix} I_{ne} \\ \alpha(\theta) \end{bmatrix} \varkappa \tag{33}$$

From the expression given in Eqs. (27)–(29), these symbolizations can be achieved as given in Eq. (34), when the fundamental matrix will be represented as X, while Y is the out factor, and $Z := [I_{ne} \;\; A^T(\theta)]^T$. Then, $YZ = \left[I_{ne} \;\; P_\mu^T \;\; A^T(\theta) \right]^T$.

$$\begin{bmatrix} \sum_{j=1}^{m} \theta_j \wp_j & \wp(\theta) \\ \wp(\theta) & 0 \end{bmatrix} = \begin{bmatrix} I_{ne} & 0 \\ P_\mu & 0 \\ 0 & I_{ne} \end{bmatrix}^T \begin{bmatrix} \sum_{j=1}^{m} \theta_j \wp_j & 0 & \wp_1 \\ 0 & 0 & (\wp^{\varsigma}) \\ \wp_1 & (\wp^{\varsigma})^T & 0 \end{bmatrix} \begin{bmatrix} I_{ne} & 0 \\ P_\mu & 0 \\ 0 & I_{ne} \end{bmatrix} \tag{34}$$

Therefore, the condition of Lyapunov stability expression in Eq. (34) is comparable with $YZ^T X(YZ) < 0$. So, the matrix YZ can be reform as given in Eq. (35).

$$YZ = P_\mu * \begin{bmatrix} 0 & P_\mu \\ 0 & P_\mu \\ \omega^{\aleph} & \alpha_1 \end{bmatrix} \tag{35}$$

But the variable X which depends on the fuzzy weighing function derivative can be solved using conservatism of LMI-based stabilization conditions as in Eq. (36). The constraint notation is $\sum_{j=1}^{m} \theta_j \wp_j = 0$ and $\wp_j + F - \wp_1 \geq 0, j \in I[2, m]$.

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$$\sum_{j=1}^{m}\dot{\theta}_j\wp_j=\dot{\theta}_1F+\sum_{j=2}^{m}\phi_j\left(\wp_j+F-\wp_1\right)\leq\dot{\theta}_1F\leq\sum_{j=2}^{m}\dot{\theta}_j\left(\wp_j+F-\wp_1\right) \tag{36}$$

So, if $\Phi_1:=\Phi_1F+\sum_{j=2}^{m}\dot{\theta}_j\left(\wp_j+F-\wp_1\right)$ and $\Phi_2:=-\Phi_1F+\sum_{j=2}^{m}\dot{\theta}_j\left(\wp_j+F-\wp_1\right)$, the stability of Lyapunov fuzzy weighing function is guaranteed by the expression given in Eq. (37).

$$(YZ)^TX_k(YZ)<0\;k=1,2, \tag{37}$$

where

$$X_k:=\begin{bmatrix}\Phi_k & 0 & \wp_1\\ 0 & 0 & \wp^c\\ \wp_1 & (\wp^c)^T & 0\end{bmatrix}$$

For the fuzzy system controller to be asymptotically stabilized, then it is given that $u=U(\theta)Q^{-1}(\theta)x$ with $U(\theta)=\sum_{j=1}^{m}\theta_jU_j$ and $Q(\theta)=\sum_{j=1}^{m}\theta_jQ_j$. The Lyapunov fuzzy system function is given as $\forall=\varkappa^TQ^{-1}(\theta)\varkappa$ and the system controller can be expressed as $u=U(\theta)Q^{-1}(\theta)x$, and the condition for stabilization $d=0$ can be finally described as in Eq. (38) with a similar derivation of LMI-based stabilization condition [41, 42].

$$-\sum_{j=1}^{m}\theta_jQ_j+A(\theta)Q(\theta)+Q(\theta)A^T(\theta)+B_u(\theta)U(\theta)+U^T(\theta)B_u^T(\theta)>0 \tag{38}$$

3.4 Implementation of non-linear consequent fuzzy controller based-greenhouse design in LabVIEW

The Fuzzy Inference System (FIS) consists of two inputs (temperature and humidity) and two outputs (electric roof and water spills). A Mamdani fuzzy logic technique was implemented in this study due to its wide acceptance and suitability for this application. The triangular membership functions were implemented for all inputs and outputs. The input 'Temperature' had membership function values of 'cold', 'normal', and 'warm', while the input 'Humidity' membership function had

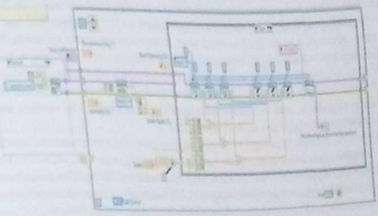

Figure 5.
Block diagram of an intelligent greenhouse control system.

values of 'dry', 'normal', and 'wet'. As for the outputs, the membership function for 'Electric Roof' signified the level of the opening for the roof. The output membership function parameter is 'closed', semi-open', and 'open'. The output 'Water Spills' represented the amount of water to be spilled by the sprinkler. This parameter has membership function values of 'low', 'moderate', and 'more'. Besides, the greenhouse control system was designed to consider each of the four major seasons (spring, summer, fall, and winter). As a result of this weather variation, each season has different membership function values for the weather conditions. The block diagram is illustrated in **Figure 5**.

4. Results and discussion

4.1 Simulation results of an intelligent greenhouse management based nonlinear control

The intelligent greenhouse control system was designed and simulated in LabVIEW using non-linear consequent for the controller. Two major interface environments were used to achieve the design of the system, the front panel, and the block diagram interfaces. The LabVIEW environment also provides a tool for fuzzy logic designs and the fuzzy logic designer has three interfaces, namely: Variables, Rules, and Test System. These interfaces respectively give the user an interface to specify the inputs and outputs of the system, provide the IF-THEN rules, and test the system to analyze the performance. In LabVIEW, an algorithm was implemented for the intelligent control of the greenhouse. This algorithm was implemented using a block diagram for the simulation of a nonlinear based intelligent greenhouse control system.

The interface has a knob that can be used to select a particular season. Also, the temperature and humidity can be altered to view various results. Selecting different values for temperature and humidity result in different outputs for roof opening and the water spills through system actuators. These outputs are determined by the fuzzy logic controller. Depending on the season selected, the outputs of the FIS will differ even with the same inputs. This is mainly because each season uses a different membership function for its decision-making. Considering these scenarios, experiments were conducted for each of the four seasons with the same input values. This was done to analyze varying results of the seasons and to examine the effectiveness of the control system. During this summer season, the dynamic sensor deployed to the environment is temperature and moisture sensors for monitoring the temperature and humidity of the greenhouse at constant temperature input of 25°C and the relative humidity of 85%. The membership function for temperature has three stages cold, normal, warm. It observed that temperature starts to normalizes from 22.5–32.5 degrees celcius to get constant temperature input. Therefore, the roof is open at 50%, and water spilled at the relative humidity of 40.1%. The simulation of fuzzy controller based intelligent greenhouse during the summer season was presented in **Figure 6**, and its fuzzy membership functions. The surface view of the dynamic system testing is presented in **Figure 7**.

In this work, a knob is designed to mimic the outside environment based on four possible weather conditions in a year (summer, spring, rainfall, winter). The constant temperature parameter set is 25°C and humidity at 65%. The membership function for temperature has three stages cold, normal, warm. During the summer, the temperature starts to normalize from 22.5–32.5 degrees Celsius to get a constant temperature value. Then, from the understanding of physics, an increase in temperature reduces humidity and relatively controls the sprinkler to turn ON and

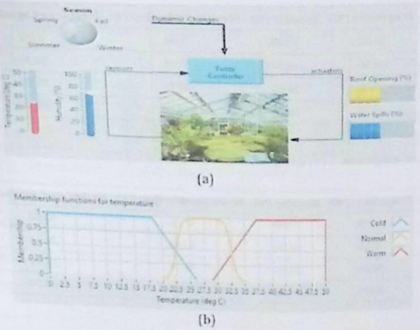

Figure 6.
A greenhouse simulation model for spring season and its membership function. (a) A greenhouse simulation model for the summer season. (b) The simulation model result of an intelligent greenhouse environment shows that the average temperature of (17.5°C) and humidity (55%) are conducive for crop growth and development without requiring roof opening or water spills.

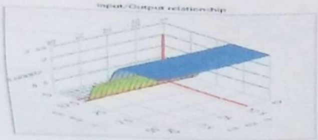

Figure 7.
Surface view of the dynamic system testing.

Series	Temperature (°C)	Humidity (%)	Water sprinkler flow (%)	Electric roof opening (%)
1	10.00	60.00	0.00	0.00
2	20.00	40.00	20.80	10.56
3	30.00	20.00	90.43	50.00
4	40.00	10.00	100.00	100.00

Table 3.
Results for the summer season.

cause the roof opening. All these calculations are handled logically by the fuzzy logic controller in the software-context based on the input and possible output variables. **Tables 3–6** presented the results obtained for summer, spring, winter, and fall seasons respectively, and the graphical representation of the results obtained is in **Figures 8–11**.

Series	Temperature (°C)	Humidity (%)	Water sprinkler flow (%)	Electric roof opening (%)
1	10.00	60.00	0.00	0.00
2	20.00	40.00	50.38	30.30
3	30.00	20.00	80.79	70.50
4	40.00	10.00	100.00	100.00

Table 4.
Results for the spring season.

Series	Temperature (°C)	Humidity (%)	Water sprinkler flow (%)	Electric roof opening (%)
1	10.00	60.00	50.00	50.00
2	20.00	40.00	80.80	70.63
3	30.00	20.00	90.70	70.63
4	40.00	10.00	100.00	100.00

Table 5.
Results for the winter season.

Series	Temperature (°C)	Humidity (%)	Water sprinkler flow (%)	Electric roof opening (%)
1	10.00	60.00	0.00	0.00
2	20.00	40.00	75.80	60.00
3	30.00	20.00	80.23	70.00
4	40.00	10.00	100.00	100.00

Table 6.
Results for rainfall season.

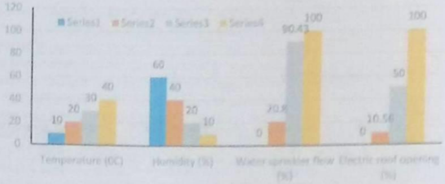

Figure 8.
Graphical representation of summer season parameters.

In this context, a knob is designed to mimic the outside environment based on four possible weather conditions in a year (summer, spring, rainfall, winter). The constant temperature parameter set is 25°C and humidity at 65%. The membership function for temperature has three stages cold, normal, warm. During the summer, the temperature starts to normalize from 22.5–32.5 degrees Celsius to get constant temperature value. Then, from the understanding of physics an increase in temperature reduces humidity and relatively controls the sprinkler to turn ON and the cause the roof opening. All these calculations are handled logically by the fuzzy

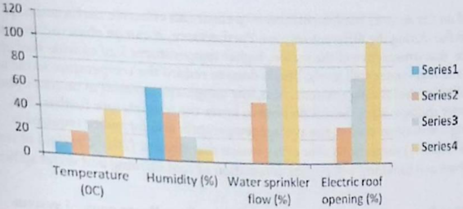

Figure 9.
Graphical output for simulation of spring season parameters.

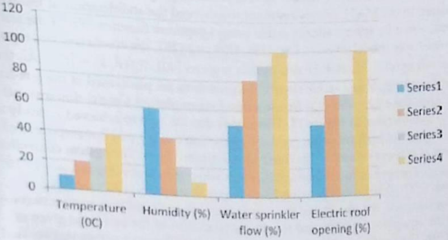

Figure 10.
Graphical output for simulation of winter season parameters.

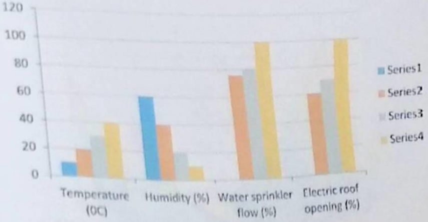

Figure 11.
Graphical output for simulation of rainfall season parameters.

logic controller in the software-context based on the input and possible output variables.

The results for each season depending on different environmental and season behavior which is processed by non-linear consequent fuzzy logic controller. This is achieved using different membership functions for each season. Since each season has its unique weather conditions and temperature requirements. The variation based on the season's implementation is to ensure an effective performance of controller during the different seasons. Furthermore, it can be observed from the results that irrespective of the season, higher temperatures lead to wide roof openings and high-water spill levels. This is done to reduce the temperature to the level specified by the farming environs. Also, low temperatures result in no roof openings or water spillage, since there is no need to lower the temperature further. But, during the summer season, the average temperature and humidity required is ($27.5^0C\&65\%$) respectively. For every season that beyond ($30.5^0C\&75\%$) of temperature and humidity will require automation of roof opening and water spilled.

4.2 Simulation results of a Lyapunov stability of nonlinear control system

The nonlinear fuzzy controller system for managing intelligent greenhouse was simulated in the MATLAB environment to achieved the stabilization of linearizing system, when its asymptotically stable using Lyapunov function. From the state-space of fuzzy model given in Eqs. (18), (25) and (26), the characteristics equation is derived as $|\ell\imath - \mathring{A}|$, and the description is given [42]. If $f(\ell, \lambda) = |\ell\imath - \mathring{A}|$, the system is universal and stable since the eigenvalues are positioned at the left-half side. Also, the eigenvalues (λ) follow a trend when plotted a multi-dimensional of $f(\ell, \lambda)$ as illustrated in **Figure 12**. This eigenvalue (λ) help to achieved a steady with better dynamic performances, good compensation quality and fast responses of the system as it moves closer to the trend of red spotted lines. The system controller undergoes processes to achieve stabilization when the eigenvalue is $\lambda = -1 * 10^2$ at periods of (0–0.50) seconds using Fast Fourier Transform (FFT) analysis.

For instance, we considered the continuous-time of nonlinear system to compute the equilibrium points and steadiness (stability) of the system as given in Eq. (39). The control system pathways based on the dynamic nature was verified in the MATLAB simulation environment for the chosen value of $g = 2$, $g = 3$, $g = 4$, and $g = 5$.

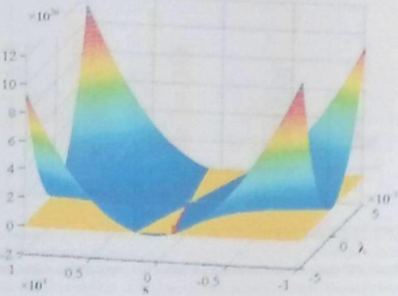

Figure 12.
A multi-dimensional design of eigenvalues $f(\ell, \lambda)$

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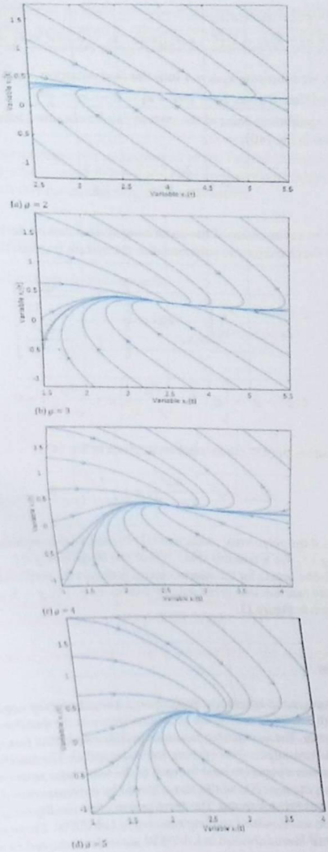

Figure 13.
Pathway line within the setpoint environment when $g = 2$, $g = 3$, $g = 4$, and $g = 5$.

$$\begin{cases} 0 = g(2 - x_1) + x_1^2 x_2 \\ 0 = x_1 - x_1^2 x_2 = x_1(1 - x_1 x_1), when\ x_1 = 0, and\ x_1 x_1 = 1 \end{cases} \tag{39}$$

Therefore, we substitute $x_1 x_1 = 1$ into the first equation, as $x_1 = 0$ does not satisfy the condition. It gives $2g - g x_1 + x_1 = 0 \to x_1 = \frac{2g}{g-1}$.

Then, the equilibrium point of the system can be obtained when $g \neq 1$, which give expression in Eq. (40);

$$\bar{x}_1 = \frac{2g}{g-1},\ \bar{x}_2 = \frac{g-1}{2g} \tag{40}$$

The set point environment of the linearizing system can be derived as given in Eq. (41), and the characteristic polynomial of the system is given in Eq. (42):

$$\dot{x}(t) = \begin{bmatrix} -g + 2x_1 x_2 & x_1^2 \\ 1 - 2x_1 x_2 & -x_1^2 \end{bmatrix}_{(\bar{x}_1, \bar{x}_2)} x(t) = \begin{bmatrix} 2 - g & \frac{4g^2}{(g-1)^2} \\ -1 & \frac{-4g^2}{(g-1)^2} \end{bmatrix} x(t) \tag{41}$$

$$\Delta(g) = g^2 + \left[g - 2 + \frac{4g^2}{(g-1)^2} \right] g + \frac{4g^2}{(g-1)^2} = 0 \tag{42}$$

This expression in (42) can be resolves as given in Eq. (43).

$$\Delta(g) = g^2 + \frac{4g^2}{(g-1)^2} g + \frac{4g^2}{(g-1)} = 0 \tag{43}$$

Therefore, if the polynomial coefficient is both positive then equilibrium point is stable when $g > 1$, else is unstable when at least one eigenvalue $g < 1$.

The simulation results for the system control pathways for nonlinear system using Lyapunov function with given stability conditions $g = 2$, $g = 3$, $g = 4$, and $g = 5$ are shown in **Figure 13**.

5. Conclusions

The greenhouse control system was implemented using the Fuzzy Logic Controller design with non-linear consequent as an intelligence in the decision-making process of the system. The membership functions include two inputs (temperature and humidity) and two outputs (roof opening and water spills). The intelligent greenhouse system was designed to cater for each of the four major seasons (summer, spring, winter, and rainfall) and this was achieved by implementing different membership functions for each season. The development of an intelligent greenhouse control system was simulated and implemented in LabVIEW. These technologies, FLC and Virtual Instrumentation in LabVIEW are widely adopted to enable computing and communication to migrate out of the gray box into ordinary objects (standalone system). However, it is significant that building of an intelligent systems to model human activities or interactions is important to the agricultural technology development. The results obtained show varying performances for each season to cater for different weather conditions. Future research will be considered incorporating a heating mechanism to raise the temperature for varying conditions and hybrid intelligent techniques using optimization technique for a better system performance.

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Conflict of interest

No 'conflict of interest' in this research.

Author details

Lukman Adewale Ajao[1*], Emmanuel Adewale Adedokun[2], Joseph Ebosetale Okhaifoh[3] and Habib Bello Salau[2]

1 Department of Computer Engineering, Federal University of Technology, Minna, Nigeria

2 Department of Computer Engineering, Ahmadu Bello University, Zaria, Nigeria

3 Department of Electrical and Electronics Engineering, Federal University of Petroleum Resources, Effurun, Nigeria

*Address all correspondence to: ajao.wale@futminna.edu.ng

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Chapter 25

An Overview of CAN-BUS Development, Utilization, and Future Potential in Serial Network Messaging for Off-Road Mobile Equipment

Hannah M. Boland, Morgan I. Burgett, Aaron J. Etienne and Robert M. Stwalley III

Abstract

A Controller Area Network (CAN) is a serial network information technology that facilitates the passing of information between Electronic Control Units (ECUs, also known as nodes). Developed by BOSCH in 1986 to circumvent challenges in harness-connected systems and provide improved message handling in automobiles, the CAN interface allows broadcast communication between all connected ECUs within a vehicle's integrated electronic system through distributed control and decentralized measuring equipment. Since the early uses of CAN in car engine management, improvements in bitrate, bandwidth, and standardization protocols (such as ISO 11898 and SAE J1939) have led to CAN utilization in various industry applications, such as factory automation, aviation, off-highway vehicles, and telematics. Alternative wired and wireless technologies have been used to connect and network with CAN-BUS (such as Ethernet, Bluetooth, Wi-Fi, ZigBee, etc.), further expanding the diversity of applications in which the serial network is employed. In this chapter, the past, present, and prospective future developments of CAN technology, with focused attention on applications in the agricultural and off-road sectors are broadly examined. CAN technology fundamentals, standards creation, modern day uses, and potential functionalities and challenges specific to CAN in the wake of precision agriculture and smart farming are discussed in detail.

Keywords: CAN-BUS, Serial Network, Agricultural Sector, Electronic Control Units

1. Introduction and Background

A Controller Area Network (CAN) in a vehicle or machine is analogous to the nervous system of a living organism. The nervous system of the body is a neuron-based network that collects signals from sensory receptors, passes chemical messages to and from the brain, responds to stimuli, and initiates actions. Expanding the analogy, sensors in a controller circuit are the equivalent of receptors, and an electronic control unit (ECU) can be visualized as a sensory neuron system

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dedicated to a specific function, bridging communication between receptors and the central nervous system. CAN-BUS systems create communication pathways between the electronic control units within a vehicle, allowing the transfer and interpretation of collected data. Prior to the invention of CAN-BUS, there was no efficient means of cross-communication between ECUs. CAN-BUS is efficient by relaying the most important messages first, through a prioritization scheme of source ID-encoded messages using the binary unit system (BUS). This is an extremely robust arrangement, with a high ability to both detect signal errors and to function when hardware is cross wired. This structure is fully distributed, which allows for a single access point for all the desirable information collected. CAN-BUS is a relatively simple, low-cost system that reduces the overall harness weight and amount of wiring needed in a vehicle, improving the integrity of transmitted data in comparison to harness-connected electrical structures [1].

While CAN-BUS has been an effective communication technology in many past and present applications, future utilization of the network system continues to be a subject of research and development. In agricultural uses, this tool aids in precision agricultural applications and in the realm of data communication within larger farm systems. Vehicle autonomy is another area in which CAN-BUS may play an important role as an inter-communication system. Additionally, there is still significant untapped potential for integrating CAN-BUS messaging into both more off-road control systems and wireless technologies.

The purpose of this chapter is to familiarize the reader with the importance of CAN-BUS in commercial off-road vehicles, applications, and future potential usage. In order to fully understand the benefits of CAN-BUS, the origins of CAN-BUS and its subsequent applications will be summarized. A high-level analysis of CAN-BUS technology, standards, and communication protocols will be presented to better familiarize the reader with essential technological concepts. Current applications of CAN-BUS and a comparison with alternative electronic control systems will be provided. A final qualitative evaluation of CAN-BUS capabilities will allow for a deeper understanding of why it is the dominant technology in modern vehicles and what innovations may be needed to expand its breadth of application in the changing technological landscape of off-road equipment.

2. History

2.1 CAN-BUS development

CAN was developed in 1986 by BOSCH as a means to overcome the limitations in harness-connected control systems [2]. Their goal was greater functionality in message communication in automobiles, which could be accomplished through distributed control. A distributed control system connects multiple, specific instrumentation into a system network that facilitates the transmission of data and information, adapting to the needs of the automation control scheme used. It combines individual, decentralized measuring control equipment into a main network node, creating an interconnected network capable of controlling a larger system [3]. In developing the CAN system, the control equipment corresponded to nodes (or ECUs), which were connected to a two-wire bus, completing the network connection. The system prevented message collisions, thereby preventing the loss of crucial information, a common issue with other existing technologies at the time.

While other technologies could achieve the goal of inter-node communication, they required complex wiring systems, with each ECU individually connected to other ECUs to provide a communication pathway [1]. The point-to-point wiring of all ECUs was unnecessarily complex and caused difficulties in data and message management. In CAN-BUS implementation, all the connections are made directly on the same area network. Through utilization of microcontrollers, the system complexity decreased dramatically, allowing for a reduction in wiring, a simplified manufacturing assembly process for connecting nodes, and an overall increased system performance. Due to the improved efficiencies and system simplicity that this technology offered, CAN-BUS became a viable alternative to the complex point-to-point wiring harnesses used at the time [4].

In 1987, both Intel and Philips developed the first CAN controller chips, the Intel 82526 and the Philips 82C200, respectively [2]. The first iteration of this technology was a chip that managed messages by assigned priorities. This allowed the more important messages to be received with significantly less delay. Notably, this first system included error detection, which would automatically disconnect faulty nodes, while still allowing uninterrupted communication between working nodes [5]. The hierarchy system allowed for the most crucial information to be passed along first, making the system particularly useful in applications with high safety requirements [1].

In early CAN development, there were two hardware implementations that cover the bulk of installations: Basic CAN and Full CAN. Basic CAN utilized a single message buffer to receive and transmit messages. The standard CAN controller implemented a specified number of message buffers (usually around sixteen), wherein the programmed algorithm read the received messages and wrote messages to be transmitted [6]. In Basic CAN, the received message is passed through acceptance filtering, which then decides whether to process a message or ignore it. Software is used to control the acceptance filtering of a node in Basic CAN. Bit masks for message identifiers make it possible to ignore certain messages by ignoring specific identifiers, in order to reduce the software load requirement at the individual nodes [7].

Compared to Basic CAN, Full CAN is a bit more complex. Every transmitted or received message is accompanied by eight to sixteen memory buffers in the Full CAN scheme. Hardware, rather than software, performs acceptance filtering in this system, reducing the overall software load significantly. Individual buffers are configured to accept messages with specific identifiers, and unique buffers for individual messages allow more processing time for the messages that are received. The transmitted messages can then be better handled according to their priority levels. Data consistency is also improved through this one-on-one buffer-to-message configuration [7]. Unfortunately, Full CAN is limited in the number of frames that can be received, and it requires more computational chips at each node than Basic CAN. Early CAN controllers by Intel and Philips were constructed under the Basic CAN or Full CAN configurations, with Philips favoring the former and Intel the latter. Modern CAN controllers combine the frame handling and acceptance filtering strengths of both, so the distinction is no longer made between Basic and Full [2].

A major milestone in bringing CAN-BUS into industry was the development of the CAN-in-Automation (CiA) working group in 1992. CiA is an international organization comprised of manufacturers and users with the goal of creating developmental content based on members' interests and initiatives [2]. One year later, the International Organization for Standardization (ISO) published ISO 11898, which defined controller area network communication protocols for the automotive industry. ISO is a non-governmental organization, without corporate affiliations, comprised of individual standards organizations from 165 nations. It develops voluntary international standards and improves the world's trading potential by providing common standards across the globe [8]. The implementation of an ISO standard for CAN-BUS was an important step in bringing coherence and marketability to the serial network system.

As the bandwidth requirements of the automotive industry continued to increase, the CAN data link layer (which will be covered in later sections) needed to be updated. BOSCH began developing the CAN FD (flexible data-rate) protocol in 2011, working in conjunction with carmakers and other CAN experts. This updated protocol surmounted two of the most restrictive early CAN limitations: the data transfer rate and payload. CAN FD allows for a bit rate (transmission speed) of up to 12 Megabits per second (*Mbps*), twelve times faster than the previous maximum transmission limit. The data field message payload was expanded up to 64 bytes in length, an increase of eight times beyond the previous payload size restriction [2]. CAN FD incorporated a simple, yet powerful ideology: when only one node is transmitting data, the bit rate can increase as no nodes need to be synchronized. The nodes are then resynchronized following the data transmission and data integrity check, just prior to an acknowledgement of data acceptance [9]. By 2015, ISO 11898 had been updated to incorporate CAN FD, and it has continued to be the standard CAN system in commercial implementations [2].

2.2 Early applications of CAN technology

CAN-BUS has played a major role in industry since its debut in 1987. In the mid-1990s, companies like Infineon Technologies and Motorola began shipping large quantities of CAN-BUS controllers to European automotive manufacturers, marking the advent of CAN utilization in the automotive industry. In 1992, Mercedes-Benz was noted as the first manufacturer to implement the controller within their processes, when CAN-BUS was first incorporated in their high-end passenger cars for engine care management [2].

BMW was next to implement CAN-BUS technology in 1995. They introduced a star topology network with five electronic control units in their 7 Series cars. Then, they took the implementation even further and employed a second network for body electronics. This allowed two separate CAN-BUS networks to be associated through gateway connections. Following BMW's example, other manufacturers soon began implementing two separate systems in all their passenger cars. Today, many manufacturers have multiple CANBUS networks associated with their production vehicles [2]. An example of vehicular integration is presented in **Figure 1**.

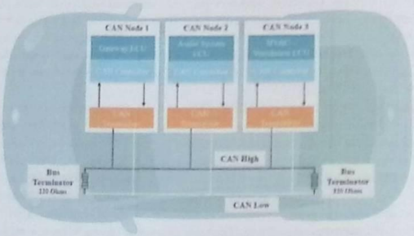

Figure 1.
Illustration showing the multiple node connections to CAN-BUS in a modern vehicle.

In 1993, a European consortium led by BOSCH prototyped a network which would later become CANopen. This project was eventually passed to CiA for further development and maintenance. In 1995, it was completely revised and became the most important standardized network in Europe within just a few years. The CANopen network protocol offers high configuration flexibility, which has allowed its installation in a multitude of applications. The networks were first used for internal machine communications, specifically in drives, but they have since been utilized in many other industries. Within the United States, CANopen has been implemented for use in forklifts, letter sorting machines, and other network processes [2].

As mentioned in the previous section, introduction of CAN-BUS into the automotive world required the standardization of protocols and testing standards to ensure CAN system conformity. ISO 11898, the first international standard for CAN, was based on the BOSCH CAN specification 2.0, and it standardized the high-speed physical layer for the system at the time [10]. As network technology continued to develop, allowing for different data transmission speeds and fault tolerances in the physical layers, new revisions to standards and interfaces for vehicle-specific applications were needed. This led to the development of SAE J1939 for heavy-duty vehicles and multiple other ISO standards (some will be covered in the CAN-BUS Standards Development section below). Due to the rapidity of CAN modification and development in the early 1990s, no error-free, complete standards or CAN specifications were available for CAN chip manufacturers. This led to the establishment of CAN conformance testing houses, where all CAN chips could be tested for compliance to the BOSCH CAN reference model using the testing plans outlined in ISO 16845 [2]. These steps were important in allowing the new technology to be widely applied in a variety of markets.

With regard to the marketing of CAN-BUS into the agricultural industry, in 2000 the German Mechanical Engineering Professional Society (VDMA) founded the Implementation Group of ISOBUS to promote the ISOBUS controller. The German Agricultural Society (Deutsche Landwirtschafts-Gesellschaft, DLG) assisted with the development of the first tests and a testing facility for ISOBUS compliance, which remains the primary test house for device compatibility. In 2009, several companies joined to form the Agricultural Industry Electronics Foundation (AEF), a non-profit organization which further promoted the use of CAN-BUS controllers, especially the implementation of ISO 11783. Since then, there have been many plug-tests organized at various locations. The first plug-test for CAN-BUS in North America was hosted by the Nebraska Tractor Test Laboratory in 2010 [11].

This review of the development of CAN-BUS and its early applications illustrates some of the current and future directions for the technology. Besides the novel use of a distributed communication network, these development efforts have truly positioned CAN-BUS as the leading serial network system in off-road vehicles. The establishment of international societies and standards has been essential in this effort. The societies are dedicated to enforcing CAN standardization across the industry and to enhancing the functionality and quality of CAN technology through research and development. These organizations will likely continue to play an important role as CAN systems are utilized in new implementations going forward.

3. Technology fundamentals

3.1 CAN utilization: messaging basics

To gain a more complete grasp on how CAN ID messaging works and how different ECUs can interpret these messages, it is helpful to understand the overall structure of CAN messages, from both a data and hardware perspective. This section covers the physical architecture of the BUS, the different components of CAN messages, CAN error-handling, a high-level breakdown of CAN layers, and provides an overview on how CAN-BUS systems support effective messaging channels.

The physical architecture or layer of a Controller Area Network includes two wires, CAN High (CAN-H) and CAN Low (CAN-L), which carry all CAN messages between ECUs and connect to BUS terminators at each end. The BUS terminators are powered and grounded, providing the necessary voltage to allow serial network operation. The most standard form of CAN wiring in modern systems is the twisted quad cabling configuration, in which a terminating bias circuit (TBC), with a power wire and ground wire, is wound together with the CAN-H and CAN-L signal wires between the two terminators [12]. Both of the signal wires have set dominant and recessive voltages that correspond to the CAN system type (high speed or low speed). The system reads the voltage difference between the two wires as a bit-value of "0" when the voltages are dominant, or a value of "1" when the voltages are recessive, creating the mechanism of sending binary messages through the system hardware [13].

A maximum of 30 ECUs can be attached to a single section of the BUS, and the overall number for ECUs connected to the network is limited to 254. The maximum number of available ECU addresses is limited to 256, because the maximum length of a data signal is 8 bytes. The 255 address is left null, and the 256 address indicates for a message to be accepted by every ECU connected to the network [12]. Since CAN-BUS is a broadcast protocol, messages are not sent to specific nodes, but rather, every ECU connected to the network receives every transmission from all other nodes on the same network. Various ECUs typically have filters on their receiving ends, so that the local computer only accepts the messages that pertain to its operational needs [14]. This open communication between all connected nodes helps to improve the manufacturing process and implementation of the system, creating vehicle-wide interconnection. Since all the nodes are linked by subsystem functions, there are no redundant connections between any two specific ECUs.

As shown in **Figure 2**, a basic CAN message has eight key parts: 1) Start of Frame (SOF); 2) CAN Identifier (CAN ID); 3) Remote Transmission Request (RTR); 4) Control; 5) Data; 6) Cyclic Redundancy Check (CRC); 7) Acknowledgement (ACK); and 8) End of Frame (EOF). It should be noted that the "CAN frame" consists of parts 2 and 5: the CAN ID and the Data [12]. The SOF is a 1 bit "dominant zero" at the beginning of a CAN message which signals that an ECU is about to send a message. This alerts other ECUs connected to the CAN to "listen" for the message transmission. The CAN ID contains information on the message priority (lower values indicate higher priority) and the source address. The identifier bit length varies by version of CAN, with CAN 2.0 being 11-bits and later versions relying on

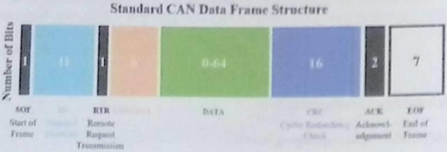

Figure 2.
CAN-BUS message structure.

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extended 29-bit identifiers. The RTR is another 1-bit piece of the message indicating whether a node is sending data to or requesting data from a specific ECU. The Control portion of a CAN message is 6 bits in length, 4 of which are the data length code (DLC), which denotes the size of the data message to be transmitted (0–8 bytes) [13]. The Data segment of the CAN message makes-up the bulk of information being communicated, and it contains all the CAN signals to be extracted and decoded for use by the receiving ECUs [5].

The four message parts prior to the Data portion are all used to give the receiving ECUs adequate information on whether to receive the data being sent and what kind of data to expect. The last three parts of a CAN message are used to ensure that the data was transmitted successfully. The CRC is a 16-bit portion of the data that checks the data integrity, while the ACK is a 2-bit acknowledgement that the CRC found no issues with the data, allowing it to pass. Finally, the EOF is the 7-bit cap on a CAN message that signals the end of the transmission [13]. A breakdown of these eight parts highlights the strength of CAN messaging, in that it provides both front-end and back-end context for the data being sent. Message types used in CAN-BUS include the data frame (a data transmission message), the error frame (a message that violates CAN formatting to signal an error in data transfer), the remote frame (a message to request data), and an overload frame (a message transmitted by an overloaded node to trigger delays) [5].

System robustness and error handling are the two major benefits of the CAN-BUS system architecture. Error handling is the methodology of detecting flawed messages that come across the CAN-BUS, in which the original sender destroys a faulty message using an Error Frame, and then re-transmits the correct message. All CAN controllers connected to the BUS listen for potential transmission errors whenever a new message is sent along the BUS [15]. When an error has been identified, the node that discovered the error will transmit an Error Flag throughout the system, halting all CAN-BUS traffic. The other connected nodes will each receive the Error Flag and transmit eight recessive bits, known as an Error Delimiter signal, to clear the BUS before taking appropriate action in response to the error. The most common response to an Error Flag is to discard the erroneous message and continue to transmit and receive other messages streaming on the BUS. This allows for what is known as fault tolerance, or the ability for the system to function around an error state [15]. An example of the error handling message structure is detailed in **Figure 3**.

Each node keeps a record of detected errors through two different registers. Errors that the ECU was responsible for sending are accounted for in the Transmit Error Counter, while faults that it detected in other nodes' messages are logged in the Receive Error Counter. Several protocols have been defined which govern how recorded errors increment or decrement the counters. When a transmitter detects a fault error in a message, it increments the register for the Transmit Errors at a faster rate than the receiving nodes increment their Receive Error registers, since

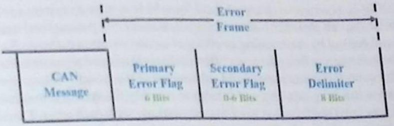

Figure 3.
A sample of an error handling message structure.

the transmitter causes system faults in most cases. When a node's Error Counter exceeds a predetermined value, the ECU enters an Error Passive state, in which its error detection activities will not be broadcast on BUS traffic for other nodes to see. When the counter rises above a second, higher preset value, it switches into a BUS-Off state, removing the ECU from participation in BUS traffic [15]. Through this process, CAN nodes can both detect faults and perform error confinement.

An Open Systems Interconnect (OSI) reference model is utilized by CAN-based network solutions. This same standard is applied across all modern communication technologies. This model is standardized in ISO/IEC 7498-1, which defines "a common basis for the coordination of standards development for the purpose of systems interconnection" [9]. The adapted CAN message model comprises three of the seven OSI layers: the first layer- the CAN physical layer, the second layer- the CAN data link layer, and the seventh layer- the CAN application layer. Typically, OSI layers 3 through 6 (network, transport, session, and presentation layers) are not explicitly implemented. It is common for the application layers in CAN to incorporate functions of network and transport layers to allow this adaption of the OSI model without sacrificing functionality [16].

Higher layer protocol functionality, which spans between the network and application layers, is an important factor in CAN network design. Network management, which includes the protocol for turning CAN nodes on and off, can be included in this functionality. Node supervision in event-driven networks is another common function in network management [17]. This supervision is required to detect nodes that are missing due to several possible fault conditions. Missing nodes could be caused from a BUS-Off state, a temporary power loss, or a permanent power loss. Application layers can search for missing nodes using one of two methods. For nodes that do not transmit messages periodically, a client/server service can be programmed so that a connected server sends a state message to the monitoring "client" after a consistent period, providing a "pulse". Any interruption to the pulse that exceeds a set time limit indicates an off-line status in that node. However, if the node does transmit messages in a periodic fashion, this detection can be done implicitly [16]. An example of this time-out utilization in error reporting is given in **Figure 4**.

One of the most significant higher-layer protocol services in CAN is breaking-up data for transmission and re-assembling it on the receiving end. While this function is typically associated with the transport layer in OSI, in CAN, this parsing of data is another role executed by the application layer. Examples of protocols that provide this service include CANopen, DeviceNet, and J1939-21 [17]. Device and network design have become simplified through the utilization of software routines that execute standardized higher-layer protocols. These protocols are typically implemented in software through protocol stacks. Standardized versions of these stacks are commonly available from a variety of manufacturers. Examples of these standardized protocol stacks include CAN Application Layer (CAL) from CiA, NMEA 2000 from the International Electrotechnical Commission (IEC), and CAN FD from CiA.

CAN-BUS, as an overarching protocol for vehicle system-to-system communication, helps the vehicle make informed decisions about component level maintenance and control by maintaining an efficient communication pathway. To facilitate effective information flow, there are often multiple levels and separate systems of CAN that control specific regions and subsystems of the vehicle. This improves information handling capacity, and it helps to simplify the system into subsets that only contain the ECUs that need to communicate with each other. There is no reason, for example, for the ECU controlling in-cab climate control to know what is happening with the left rear tire pressure sensor. These controllers are divided onto different specialized networks, enhancing system efficiency.

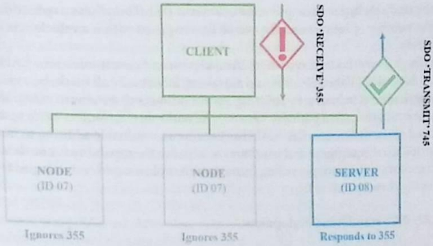

Figure 4.
Implicit message time-out reporting utilizing CANopen.

In addition to separating networks into subsystems, there are also different types of CAN-BUS systems that allow for different speeds of communication. The high-speed CAN system uses the CAN-H and CAN-L wires described above and can communicate at speeds up to 1 *Mbps*. The ECUs that require this high communication speed are safety critical systems, like the engine electronic control unit, the brake controller, and the air pollution control systems [12]. These are wired in a linear serial bus configuration terminated by resistors. The other type of CAN-BUS system commonly used is low-speed CAN, which can only reach communication speeds of up to 125 *kbps*. This is an eighth of the high-speed system rate and is appropriate for fault-tolerant or comfort systems like cab climate control or interior lights. A star serial bus configuration may be used, where multiple CAN applications are terminated at nodes [4]. By splitting-up the networks, there is a higher level of reliability for safety critical systems to get their messages broadcast across the network. This can aid in the avoidance of accidents or in notifying a driver of an in-process component failure, like the loss of engine oil pressure.

To further improve efficiency of the CAN-BUS system, every ECU on the network is also assigned an arbitration ID, or an identification number. This ID dictates which ECU is given priority in the case that there are conflicting messages or messages sent at the same time. This priority framework is a large part what makes CAN so efficient. Important messages from the engine regarding fuel input, for example, are not delayed by a message from the oil pump that oil life has decreased by one percent. In having an established priority level of messages, the system can be sure that system-critical messages are broadcast and received across all interconnected ECUs. This system of broadcasting the highest priority message has been a main contributor to the success of CAN-BUS technology and its dominance in the market.

While CANs are effective at communicating data between ECUs, they can also be utilized to record the operational metrics of a vehicle. Instead of directly measuring the data with precision instruments, approximate results can be calculated using the theoretical relationships between a specific metric and other parameters that are measured with internal sensors on the CAN. These internal sensors are commonly found in plug-and-play tools that are widely available on the market for on-board processing and diagnostics. They generally have low customizability, but they are very simple to install when compared with more specialized, auxiliary sensing equipment [18]. While estimates from these embedded controllers are inexact, very accurate measurements can be obtained via this method, by first calibrating the internal sensors with precision external sensors, as shown in Polcar, Cupera, and

Kumar's study on fuel consumption measurement [19]. This allows a reduction in both the number of sensors and the overall cost required within a vehicle's control system.

Through its methods of system interconnection and communication, CAN-BUS has revolutionized data collection and autonomy in virtually all markets, especially in the agricultural industry. By splitting-up the various subsystems to create an efficient communication pathway between the multiple electronic control systems that need to communicate, CAN-BUS has become an invaluable addition to modern agricultural equipment and continues to advance the capability for on-board real-time data collection, providing farmers with sophisticated technologies for improving their operations.

3.2 CAN-BUS standards development

Thus far, this chapter has made references to CAN standards, such as ISO 11898 and SAE J1939, but it has not given an explanation as to why there are different standards for different vehicle types. This section will discuss the purpose and need for developing such individual industry standards, as well as introduce some of the most important CAN standards in industry today, especially with respect to agricultural vehicles.

As previously mentioned, controller area networks function using a serial communication protocol, making it a useful pathway for passing digital data. However, without a standard for interpreting and forwarding the data, no useful information or actionable processes can be gleaned from it. Using the analogy of a telephone, CAN would be equivalent to the hardware and telephone lines used to connect the voices of two individuals, while the standard is the language used to make the communication meaningful [5]. Just as it is important that the individuals on opposite ends of the telephone line use the same language conventions to interpret each other's speech, the same is true with standard compatibility within a vehicle's system. Many components in a single vehicle are produced by different manufacturers, and standards allow the ECUs of these various modules to function and communicate on a common network.

The first standards were focused primarily on CAN usage in automobiles, as engine care management was the original target market for usage [2]. As off-road and heavy-duty vehicles carry-out entirely different mission profiles from passenger cars, with respect to loads, implement usage, and speed, it was not possible to apply the same "language" for priority and layer management in these vehicles. This led to the evolution of application-specific standards for the vehicle manufacturing industry. To give some more context for what these standards entail, ISO 11898, SAE J1939, and ISO 11783 will be covered briefly.

ISO 11898 was released in 1993. It was initially divided into two parts, and a third part was added later. This standard covers the data link layer, the physical layer for high-speed medium attachment (HS-PMA), and the physical layer for a fault-tolerant, low-speed, medium-dependent interface. ISO 11898-1 gives the specifications for creating an interchange of data between the modules of the CAN data link layer [10]. It also specifies the two main format options, the Classical CAN frame format and the CAN Flexible Data Rate format, the latter of which was introduced in 2012. While Classical CAN supports a maximum bit rate and payload of 1 *Mbps* and 8 bytes per frame, respectively, the Flexible Data Rate frame format extends the allowance for both bit rate and payload beyond these original limits. The general architecture of CAN is also described in this ISO standard in terms of the OSI layers mentioned previously. It contains specifications for both the logical link and medium-access control sub-layers, as well as the physical coding sub-layer [6].

ISO 11898-2 gives the specifications for HS-PMA, which is a serial communication protocol that allows for real-time control of components in vehicle systems by multiplexing data for immediate use. The standard formalizes HS-PMAs with low-power mode and selective wake-up options [20]. ISO 11898-3 additionally covers the set-up of a data exchange between the ECUs of a vehicle utilizing CAN [21].

SAE J1939 was developed by the Society of Automotive Engineers (SAE) in 1994, and it establishes how nodes transmit data on the CAN-BUS in heavy-duty vehicles [22]. J1939 provides a common communication language across heavy equipment from different manufacturers, allowing a wide range of equipment to work with each other and enabling consistent data logging across heavy-duty and off-road vehicles. Although the first standards development papers on J1939 were drafted in 1994 (J1939–11, J1939–21, J1939–31), it was six years before the initial top-level document was published. After this, controller area networks were officially included within the language of the standard. In 2001, J1939 replaced the older standards SAE J1708 and SAE J1587. This standard, along with its accompanying documents, has since become a wider industry standard and is currently utilized for applications across multiple industries, including agricultural machinery, construction equipment, forestry machines, maritime ships, mass transportation, material handling, and military applications [1].

There are several key characteristics which define SAE J1939. Its bit rate, or the speed at which messages travel across the BUS, was originally set at 250 *kbps*. More recently, the standard was updated to support a faster bit rate of 500 *kbps*, and the identifier (ID), or unique name of each message, was extended to 29 bits. The message identifier segment, in addition to describing its data content, message priority, and indicating the source address, is also used in J1939 to specify the destination on the network [23]. The primary differentiation in message composition from other CAN systems comes from the Parameter Group Number (PGN). This 18-bit PGN is a function-specific frame sandwiched between the first 9 and last 2 bits of a traditional 11-bit CAN ID, providing more detail regarding the message content [24]. The J1939 message parameters within data bytes are identified by Suspect Parameter Numbers (SPNs). SPNs correlate to specific PGNs, with their encoded data designated by bit start position, bit length, scale, offset, and units. These PGN-specific details are used to extract desired SPN data and convert it to meaningful physical values [25]. An illustration of the J1939 message structure is shown in **Figure 5**.

Development of ISO 11783, a CAN-based agricultural bus system by Landwirtschaft Bussysteme (LBS), began in the early 1990s with the German DIN 9684 standard. The first commercially successful LBS combined the DIN 9684 virtual terminal (VT) concept with J1939 protocols and was internationally standardized as the ISO 11783 series [11]. The accompanying BUS system detailed in this standard is commonly known as ISOBUS. This standard consists of ten specific parts, including: 1) the general standard for data communication; 2) physical layer; 3) data link layer; 4) network layer; 5) network management; 6) virtual terminal; 7) implement messages applications layer; 8) power train messages; 9) tractor ECU; and 10) the task controller & management computer interface [14]. The communication protocols define messaging between the tractor and implement electronic systems through CAN. These, combined with the serial data network, regulate the methodology of data transference between actuators, control elements, display units, information storage systems, and sensors, allowing the tractor to control an implement through the virtual terminal (VT).

The VT is one of the most important features of the ISO 11783 standard, as it allows the operator to interface with the tractor and implements by both viewing real-time data and providing user inputs. The VT acts as a slave to individual ECUs,

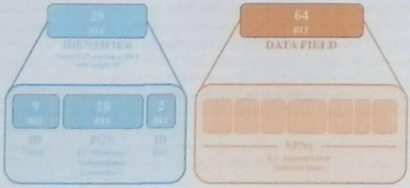

Figure 5.
SAE J1939 message structure.

each of which secure terminal connectivity to display informational data and collect operator inputs according to their individual protocol. The operator can choose which operational data to display, while each connected ECU continues to operate as if the VT were dedicated solely to its specific function [14]. This pathway makes it possible for the operator to have greater control over the functions of an implement, such as sprayer nozzle flow, combine cylinder rotational speed, or cultivator attachment height, depending on input from implement sensors. This eliminates the need for a separate control box for the implement and provides a single terminal controlling all information flow to the operator [11] . The ISOBUS is based on CAN running at 250 *kbps*. It uses twisted non-shielded quad cable and high-speed transceivers (same as ISO 11898). A 9-pin connector on the tractor is the only required point of contact between it and an implement with an ISOBUS compliant network cable.

This overview of CAN communication and standards has presented a cursory background of the technology fundamentals associated with the serial networking scheme, as well as some brief mention regarding how it is implemented. The next section will go into greater depth on how CANs have been utilized in industry, its potential connection to other network technologies, and how its usage could be expanded in the future.

4. Implementation

4.1 CAN-BUS by industry application

Although controller area network systems were originally developed for the automotive industry, they quickly became popular in other areas. CAN-utilizing industries include large over-the-road trucks, forestry, industrial factory automation, aerospace, and many others. In the aviation industry, the high-speed CAN protocol ISO 11898 is widely utilized, along with ARINC 825, a protocol created specifically for the aviation industry. The effort to create a CAN-based standard for communication in aircraft was initiated by Airbus and Boeing and was advanced by the Airlines Electronic Engineering Committee (AEEC) through their CAN Technical Working Group [26]. Several design targets were set while developing this protocol, including CAN functionality as either a main or ancillary network, an allowance for local CAN network integration into the wider aircraft network, and interoperability and interchangeability of CAN connected Line Replaceable Units (LRUs). Other design mandates were to maintain flexible configuration options; establish a simple process for adding, deleting, or modifying BUS ECUs; and simplify systems' interconnection protocols [26].

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CAN-BUS systems also play an important role in both modern factory automation processes and testing facilities. Since CAN design is based on distributed control principles, it has been effectively used in manufacturing facilities to connect the essential control systems dispersed throughout a plant. Through the use of human machine interfaces (HMIs), operator inputs can be translated into instructions that a programmable logic controller (PLC) dispatches onto the BUS, allowing the remote operation of equipment ranging from sensors to actuators. This process allows the testing of new input parameters prior to execution on specific equipment and is a viable option for increasing process safety [27]. Use of CAN on assembly lines as a quality check is also becoming more common and is especially important on a line manufacturing a customizable product. Certain specifications are programmed for each checkpoint of product assembly, which are then broadcast on the CAN between machines to provide quality validation for the operators throughout the manufacturing process. CAN-BUS is also a practical option for connecting security and environmental control systems across a facility, due to both high bit-rate and inexpensive installation [27].

Returning to CAN use in the off-road vehicle market, virtually all modern agricultural machines incorporate CAN-BUS systems. Improved vehicle diagnostics, less complex design of electronic circuit controls, and advanced implement management are all benefits that CAN-BUS technology brings to the agricultural sector. CAN-BUS systems allow for high precision in machinery performance and logistics information. These metrics help to estimate operational cost and projected size in downstream operations. Specific measurement of other metrics, including fuel consumption, engine load, and average operating speed can also help supply chain managers maximize field and transport efficiency, while designing overall equipment solutions at a lower cost [28].

Displays within the cab allow the operator of the vehicle to view real-time data and information, as the vehicle is collecting it. These displays show the current location of the vehicle via GPS, the instantaneous fuel consumption rate, and other performance metrics that help the operator make intelligent decisions in order to maximize the efficiency of the vehicle. The John Deere Gen4® display shows many attributes, such as the instantaneous fuel economy and location of the vehicle within the field, but it also communicates with other vehicles in the same area to share guidance lines, coverage maps, and applied data in order to work the field efficiently [29].

The display associated with Case IH's Advanced Farming System® (AFS®) product, like the Gen4® display, is able to show the location of the vehicle within the field [30]. Using GPS and wireless data networks, it is also possible to check the performance of each vehicle from computers located away from the field. AGCO uses Fuse®, which is much like the Gen4® display and AFS®. It shows various data on how to improve the efficiency of the specific field operation, and it includes a seed and dry fertilizer monitoring system, which alerts the operator immediately, via the display, if there is a physical delivery blockage.

Aside from the role CAN-BUS plays in system-to-system communication within a vehicle, the serial network technology has also been integral in the advent of telematics. Telematics is a sector of information technology concerned with how data moves between machines over long distances. Incorporating telematics technology into a vehicle or fleet of vehicles provides the opportunity to utilize collected data outside the scope of an individual machine's operation by integrating it into a server network for wider usage and analysis. While CAN-BUS is not the sole technology responsible for telematics, it serves an important role in communicating large quantities of data that are eventually converted into valuable information for end users [31].

The general architecture of a vehicle telematics system begins with a Telematics Control Unit (TCU), a telematics cloud server, and front-end applications (Apps) through which the end user accesses captured data. The TCU is a microcontroller that manages data collection, communication, and memory through interfacing with different hardware and software modules. It provides connection ports to CAN-BUS, GPS, General Packet Radio Service (GPRS), battery, and Bluetooth modules, while maintaining a memory unit, a Central Processing Unit (CPU), and communication interfaces to Wireless Fidelity (Wi-Fi), cellular networks, and Long-Term Evolution (LTE) networks [31]. As the central component to a telematics system, the TCU accomplishes the tasks of gathering all the desired data and information from its various connections, synthesizing the information, and communicating to the cloud for use elsewhere. Focusing specifically on the CAN interface, a TCU utilizes the CAN-BUS as a pathway to collect the requested information from the ECUs, as programmed into its operating algorithm. This information acquisition could include any sensor data such as fuel consumption or vehicle speed. By converting the data from the CAN protocols, the TCU can then transfer this data to the telematics cloud server for further post-processing, after which, a user would be able to access the data.

The most common usage of telematics across all industries is within fleet management systems. This data collection process allows managers to optimize fuel usage, monitor vehicle down-time, analyze vehicle processes, and track operators driving a specific vehicle [31]. However, different companies also try to bring unique advantages to their telematics packages, which normally materialize in the form of a specialized management software. For construction and forestry equipment, Caterpillar utilizes a company-specific telematics system called ProductLink®, which has both cell and satellite transmission options, paired with their user interface VisionLink®. The focuses in these systems include the reduction of idle time and elimination of catastrophic failures through the reporting of fault codes [32]. John Deere provides customers with the option of a subscription package to the company's telematics network JDLink®, which is customizable to include mobile connections, In-Field Data Sharing®, Operations Center® (where data is synced every 30 seconds to keep it safe and secure), and other features which provide greater connective awareness of interdependent operations [33]. Case IH takes connectivity to a more automated level with their AFS® product, which has options for auto-guidance steering in tractors and combines using AFS AccuGuide® and AFS RowGuide® to aid in year-to-year repeatability. Their AFS Pro® system monitors several operational metrics and can manage ISOBUS implements [30, 34]. Utilizing CAN-BUS as a communication platform for mobile data transfer has greatly increased the capacity for utilizing data to drive decisions and functions.

In 2009, Agritechnica launched the Isomatch Tellus® VT. This allowed for the operator to observe two ISOBUS machines through one terminal, allowing for the simultaneous control of functions on different platforms. The possible connections to this terminal included a 15 pin ISOBUS, a power connector, an additional 9 pin extension connector, 4 USB interfaces, Bluetooth, Internet dongle, EIA-232 port for GPS, and others. Later, software packs such as ISO-XML were added to the VT [11]. Another example of user-focused technology is the Opus A3 CAN-BUS operator panel series from Wachendorff Elektronik, which has two CAN-BUS ports and is specifically designed for outdoor applications that include agricultural machinery [35]. As is evidenced by many of the applications in industry discussed above, different interface technology with CAN-BUS has been important in broadening its usage in a variety of fields. Further discussion of both wireless and non-wireless alternatives to and potential connection points with CAN are explored in the next section.

4.2 Alternative connectivity and networking to CAN-BUS

Different kinds of interfaces have been specifically developed to allow the conversion of CAN data into a format for Internet of Things (IoT) communication. Two specific technologies of note are CAN-Ethernet, and CAN-Bluetooth converters. A CAN-to-Ethernet converter allows the transfer of data in both directions and may be utilized in CAN-BUS monitoring, two-way remote CAN-BUS monitoring, and synchronization [36]. The firmware on such a converter contains both a communication device and a web server. The web server manages the protocol conversions, and the communication device provides the user interface. By combining two CAN-Ethernet converters, two CAN networks can be synchronized, allowing connection between CAN networks on different machines and in remote locations. This may be scaled-up further, or a custom software can be programmed to allow the converters to communicate directly to a specific IP address [36].

A CAN-to-Bluetooth gateway, unlike the ethernet connection, can transfer wireless data directly to a mobile device, using classic Bluetooth standards for Android devices and Low Energy (BLE) for Apple IOS. As with an ethernet converter, when the devices are used as a pair, a bridge for CAN data can be created for the end-user to access [37]. The ISOBlue 2.0 is an example of technology under development that utilizes Bluetooth principles. Currently being researched in the Open Ag Technology and Systems Center (OATS) at Purdue University, it is an open-source hardware product that connects agricultural machinery to the Cloud [38]. Other interfaces that allow CAN data conversion into different forms have been important tools in making telematics technology viable for off-road agricultural equipment. CAN Logger CLX000, which works between CAN and OBD2, is one such example [39].

Additional wireless technologies that have been used to interface CAN-BUS systems to IoT devices include ZigBee and Wi-Fi. These technologies also function as standalone networks for intra-vehicle and inter-vehicle communication [40]. Similar to the CAN data converters for Bluetooth and Ethernet, ZigBee and Wi-Fi converters have also been utilized to take advantage of their respective benefits in bandwidth, data transfer rate, security, and cost. More detail on each technology's specific advantages is presented in **Table 1**.

ZigBee is a globally available, wireless networking standard initially created as a home-area network for the control and monitoring of connected devices [41]. ZigBee is beneficial for sensor and vehicle network applications, due to its affordable installation and use cost, extensive battery life compared to competing devices, minimal maintenance, security and reliability, and small physical device footprint [41]. ZigBee was built on the IEEE 802.15.4 technical standard, which defines the physical layer (PHY) and medium access control (MAC) sublayer for low-data-rate wireless personal area networks (LR-WPANs) [45]. CAN-BUS-to-ZigBee conversion has demonstrated benefits in flexibility, convenience, and ease of use in system

Wireless Technology	Installation Cost	Bandwidth Capability	Data Rate	Security
ZigBee	Medium	Medium	Low	Moderately Secure
Bluetooth	Low	Low	Low	Less Secure
Wi-Fi	High	High	High	More Secure
UWB	Low	High	High	Moderately Secure

Table 1.
A comparison of wireless technologies capable of interfacing with CAN and IoT devices [41–44].

installation, adding and removing nodes, system updates, and expanded network construction [42].

Wi-Fi is a popular wireless technology for CAN-BUS interfacing and IoT communication. Wi-Fi falls under the IEEE 802.11 standard, which is part of the broader IEEE 802 technical standards for LAN and defines MAC and PHY protocols for applying wireless local area network (WLAN) computer communication [46]. This standard also specifies common radio frequency bands that Wi-Fi can communicate on. These include but are not limited to 2.4 *GHz*, 5 *GHz*, 6 *GHz*, and 60 *GHz* frequencies [46]. Wi-Fi offers a high data rate of up to 54 *Mbps* and a large bandwidth capability [43]. The most common application for Wi-Fi to CAN-BUS interaction is vehicle-to-cloud telematics services, as discussed in the previous section. On-vehicle Wi-Fi networks also allow for remote control of vehicle systems and provide capability for varying levels of autonomous control. On-vehicle Wi-Fi networks also allow for sending CAN-BUS data from vehicle-to-vehicle or across several vehicles simultaneously.

Ultra-wideband (UWB) is another wireless technology being researched for vehicle communication systems. UWB is a low-power radio protocol specifically created to improve the location accuracy of wireless technologies. UWB transmits data across a short distance and measures the time it takes for a radio signal to travel between the sending and receiving device [46]. This is similar to the time-of-flight (ToF) method used with radio detection and ranging (RADAR). A UWB transmitter sends billions of radio pulses across a wide-spectrum frequency of 7.5 *GHz*. These pulses are then translated into usable data from a UWB receiver. While UWB is not commonly used in conjunction with CANBUS, it has been studied for use in autonomous vehicle navigation and path localization [44].

The continuous development and improvement of autonomous vehicle technology necessitates an increased demand for greater bandwidth and connectivity requirements, while still providing an allowance for high system complexity. System complexity in this case could be defined as the added latency from the connected network devices. As many aspects of the interconnected vehicle networks continue to grow, management and network understanding also become more complex. Such aspects include a number of features, routing table configurations, system security, firewall protections, and others [47]. One of the most promising alternatives to vehicle CAN networks are automotive ethernet-based networks. The market for automotive ethernet is expected to increase by 22% from 2019 to 2026 [48]. High bandwidth capabilities and improved cost efficiency are two major benefits to automotive ethernet networks. Instead of a priority-based protocol, ethernet utilizes a Carrier Sense Multiple Access with Collision Detection (CSMA/CD) strategy [49]. This defines the appropriate device response when multiple control units simultaneously attempt to use a data channel and encounter a data collision. Susceptibility to radio frequency (RF) interference, the inability to provide latency at very high frequency, and synchronization issues between timing devices are potential challenges with automotive ethernet network implementation [48]. Currently, the primary consumption of Ethernet technology in vehicles is enabling personal use of the Internet. Ethernet provides rapid data transfer speed, making it ideal for data intensive applications. However, Ethernet does not adapt well to internal failure, as seen in **Table 2**. A potential associated cost with Ethernet demand increase is the expensive coated wiring needed to provide such high bandwidths.

One type of automotive network communication protocol is FlexRay. FlexRay is a network standard for automotive systems, based on a flexible high data transmission rate, high-speed bus system, like CAN FD [48]. FlexRay is designed for communication of efficiency-type applications in the vehicle. This is due to FlexRay's high complexity allowance and bandwidth. At 10 *Mbps* on two dual channels, FlexRay can provide up

Network Type	Installation Cost	Bandwidth Capability	System Complexity	Fault Tolerance
CAN	Medium	Low	High	High
FlexRay	High	Medium	High	Medium
MOST	Medium	Medium	Medium	Low
Ethernet	Low	High	Medium	Low

Table 2.
A comparison of CAN characteristics with competing technologies [48].

to 20 *Mbps* of bandwidth, making it optimal for systems such as steering and brakes. CAN shows advantages over FlexRay primarily in cost and error handling [50]. Due to FlexRay's robust complexity and bandwidth, its cost is far greater than CAN, on a value per baud rate basis. Although CAN does not generate data transfer rates as fast as FlexRay, it is better suited for the majority of smaller jobs at a far lower cost [50].

Another type of automotive network is MOST (Media Oriented System Transport). MOST provides very fast data transfer at over 24 *Mbps*. This is because the system was designed to transfer media information within luxury cars, such as GPS, radio, and video systems. MOST has comparable speeds to Ethernet and is more common in automotive applications. However, it handles much less system complexity than CAN and FlexRay, limiting its potential applications [51]. MOST is equipped with plastic optical fiber in its physical layer, which limits electromagnetic interference, thus providing faster speeds and significantly less signal jitter. CAN and MOST have comparable costs, but CAN is better suited for more versatile and sophisticated operations [48].

Overall, CAN shows the most versatility of these four main alternative systems. FlexRay is useful for safety systems, due to its high complexity allowance and multiple channel scheme, but it is a higher-cost system by a significant margin. MOST provides one of the best options for media and information transmission, with a faster data transfer rate than two of the other technologies reviewed [50]. However, MOST cannot be used for highly complex systems. Ethernet provides the fastest data transmission speeds of all the options compared, but it is limited by low complexity allowance and adaptability. CAN, while moderately priced, shows high adaptability to complex systems, while providing useful data transfer in a variety of applications [48]. An example of an interconnected system utilizing these networks in a passenger vehicle is shown in **Figure 6**.

4.3 Prospective areas for CAN technology inclusion

Currently, CAN-BUS is used in autonomous vehicle development to gather data from all electronic control sensors and consolidate it onto a single network. By gathering the data into a unified structure, the overall system controller can easily make decisions that affect multiple sub-systems at once. This data availability, combined with swift processing, is a key component in the safe operation of autonomous vehicles both on the open road and off-road. This centralized system data stream allows for advanced control of smart engine sensors, which provide more efficient management processes. The data handling capability of smart controllers is still an area in need of concentrated improvement. Present research is looking into robust solenoids and other embedded sensors to control valve timing, coolant flow rate, compression ratio, and other key processes in engine operation [52]. Integrated development of these smart controllers with CAN will be crucial to ensuring the safety of autonomous vehicle function execution and travel.

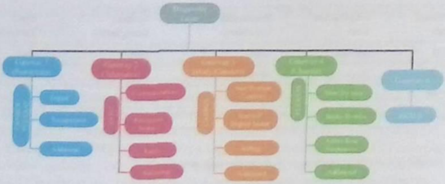

Figure 6.
An example of a FlexRay application.

While large scale agricultural mechanization has been associated with various negative environmental impacts, from soil compaction to harmful exhaust emissions, the advent of digital agriculture has played a key role in increased efficiencies and technological progress within the farming sector, reducing those detrimental elements. The utilization of CANs for improved operation is a research area where further development could have a significant impact with respect to environmental effects. For example, some of the most common technologies for limiting emissions have associated environmental costs that detract from ecological benefit. Though Exhaust Gas Recirculation (EGR) decreases NOx emissions, it simultaneously increases specific fuel consumption to lower engine efficiency. Similarly, the post-combustion treatment Selective Catalytic Reduction (SCR) results in better emissions efficiency, but consumes a urea solution that increases freshwater eutrophication risks [53].

Since fuel consumption is primarily dependent on engine speed and torque, it is possible to reliably decrease emissions with the application of alternative driving techniques optimally suited to specific drive train design and implement load [54]. However, the plausibility of deriving accurate efficiency metric assessments is limited due to present data scarcity. Current methods for Life Cycle Assessment (LCA) studies provide unreliable results because average conditions, such as soil texture, field shape, soil moisture, implement transfer difference, and engine features, have traditionally been utilized in lieu of actual conditions to estimate environmental effects [55]. CAN is advantageously positioned to help address both the data deficiency and inadequate LCA techniques, due to its data collection and communication strengths. It is possible, for example, that performance metrics could be improved through intelligent sensor solutions that can measure slippage and soil compaction at the wheels of a vehicle and attached implement [13, 54]. These sensors could communicate with sensors in the drivetrain to adjust the effective gearing ratio in real-time, reducing soil compaction and preserving the long-term viability of the soil.

An example of an instrument that, when paired with CAN-BUS communication, could be useful in achieving such operational efficiency objectives are inertial measurement units (IMUs). An inertial measurement unit functions as a sophisticated accelerometer/gyroscope combination. It boasts near zero drift between different operating conditions, and its use of magnetic fields allows it to double as an "electronic compass". The IMU allows for communication across many different CAN-BUS networks to help the tractor, or any vehicle, make decisions about how to alter the driving style for the terrain to limit "dynamic pitch and roll" through open system communication [52]. While this specific system is not currently implemented on tractors and other off-road vehicles, there is room for its introduction in the emerging field of agricultural autonomy.

Smart agriculture and digital farming practices have gained popularity in the previous decade. These techniques are precursors to a transformative implementation of information technology in the farming world. Going forward, more advanced software systems will use information collected from CAN communication devices to aid in the optimization of machinery designs and more accurate load, use-profile, and duty cycle representations of vehicles and implements [18]. Future applications for CAN-BUS technology include IoT, Edge Computing, and swarm machinery automation, as well as complex control of electrical and electric-hybrid machinery.

IoT implementation in the agricultural sector has gained enormous traction in recent years, as a result of its high potential for cross-brand interoperability, scalability, and traceability. The different types of IoT tools being applied are continuing to evolve, increasing the overall adaptability and variety of available systems to end-users [56]. IoT systems are currently being implemented on vehicles from John Deere, Case New Holland (CNH), AGCO, and others. Future IoT device use on agricultural equipment will likely be in conjunction with multiple on-board network systems. Local storage or cloud computing will be necessary to store and process the vast amount of data created by this potential technology [57]. Data processing on-board the vehicle, near the working equipment, is referred to as 'edge computing' [56, 58]. It is highly probable that agricultural vehicles will eventually be able to perform a variety of complex, agronomic tasks from a preprogrammed routing structure, through the combined utilization of both IoT and EC technologies.

In addition to on-vehicle IoT technologies, it is probable that field embedded (or in-situ) IoT sensors will also be able to communicate with larger on-farm networks [59]. Several of the previously discussed network configurations are possible whole-farm network options. These include cellular (4G, 5G, and beyond), Wi-Fi, ZigBee, and UWB. For example, real-time soil moisture can be obtained from field-based, connected sensors to create a variable-rate prescription map [60]. Utilized in conjunction with mobile soil penetrometer readings, an accurate map of soil compaction risk can be created. This could allow farmers to tailor their tillage operations to specific areas of the field, as well as control vehicle traffic.

Cutting-edge networking research is also being done with robotic and swarm machinery automation [61]. IoT technologies and improved connectivity will allow
for the introduction of robotic swarm farming techniques. Swarm farming inc
porates multiple, small-scale robotic platforms that perform farming oper
autonomously in place of larger, manned agricultural equipment. This f
strategy, paired with a predetermined path-planning algorithm optimi
machines will navigate throughout the field, could allow for near-con
operation. Additional benefits could include a centralized command
controlled by a single system manager and a significant reduction in t
skilled labor [62]. The possibility of substituting the modular vehicle d
swarm farming for traditional larger equipment will depend on cost, co
system productivity, and accuracy. Farmers will demand a significant retu
investment and the reliability that they have come to expect from their current machinery. A potential difficulty for CAN-based systems is the large bandwidth requirement for incoming and streaming data. Another potential challenge involves communication protocol differences between traditional CAN-BUS data and more memory intensive data collected from advanced machine systems, like perception engines and central processor-based codes [63]. Future developments in CAN-BUS technology should focus on addressing these weaknesses to improve adaptability to upcoming applications.

A major concern in the future of agricultural CAN use, machinery networking, and machine system automation is cybersecurity. Although increased digitization, automation, and precision services have tremendous potential to establish sustainability and profitability in farming systems, the influx of interconnected information technology simultaneously opens the market up to new areas of susceptibility, security risks, and potential targeted cyber-attacks [58]. Mission-critical systems are becoming more reliant on internet connectivity, such as controlling farming implements remotely through the ISOBUS with linked management software. Local Area Networks (LANs) have become a requirement in smart farming to enable system/device access to the data and services that control their functions [64]. This increased dependence of agricultural operations on cyber-physical systems has led to the development of new, novel threats and challenges that can be analyzed in two categories: information technology and agricultural production [58].

From an informational technology standpoint, some of the main threats are unauthorized access of resources/databases under use of falsified identity, interception of node data transfer, facility damage or downtime, malicious data attacks from malware, and compromised control systems to negatively impact decision-making [58]. Due to the nature of modern networked food systems, targeted or accidental disruption of time-sensitive agricultural processes could have a significant economic impact on a global scale. The threat of a concentrated hack on the agricultural sector has become more tangible with the analysis of cyber-security breaches in recent years, such as the 2017 infrastructure meltdown of Maersk shipping [65]. The vulnerability of Wireless Local Area Networks (WLANs) to direct cyber-attacks is already a generally recognized problem across all industries [66]. Demonstration of the damage potential in a Denial of Service (DoS) attack has been shown in the research of Sontowski et al., by disrupting in-field sensors and obstructing device network connectivity in smart farm operations [67].

Though the hacking activities of malicious actors is a highlighted concern in cyber security, there are also a number of risks associated with agricultural production that stem from physical layer vulnerabilities and limited user knowledge. The harsh environment in which agricultural equipment is used (including extreme weather conditions, dust concentration, and highly variable humidity/temperature fluctuation) can cause power failures or sensor damage [64]. Technology signal interference from other agricultural equipment, such as the high voltage pulses from Solar Insecticidal Lamps (SIL), can also lead to malfunctions and data loss [58].

However, one of the most common threats to cyber security is inadequate adoption of safety procedures by farmers who lack full awareness of device functionality. From research conducted by Nikander et al., farmers are often ill-equipped with time and resources to build LANs with appropriate network equipment, topology expansion planning, and protection software/hardware [64]. This leads to networks that are at risk of system losses due to hardware issues and human error. The adoption of countermeasures to security risks, such as authentication & access control, cryptography, key management, and intrusion detection systems, is dependent on end-users understanding the importance of cybersecurity, and better fail-safe mechanisms within hardware [58, 64]. These concerns highlight the importance of advancing security protocols in CAN-BUS systems, and it is likely that this will be a targeted focus in the future of CAN developments.

5. Conclusions

Key points from this chapter included the following:

- CAN-BUS has played a major role in industry since its debut in 1987 for its groundbreaking use of distributed network principles.

- The establishment of international societies and standards positioned CAN-BUS as the leading serial network system in all vehicles.
- CAN-BUS provides efficient and dependable communication pathways through front and back end context in messaging, error confinement, higher-layer protocols, and subsystem differentiation.
- CAN-BUS has revolutionized data collection and analysis in multiple industries, especially in the agricultural sector.
- When paired with wired or wireless technologies, CAN is an advantageous communication pathway for expanding the reach of data communication beyond point source limitations.
- Challenges for future CAN iterations include increasing bandwidth and security measures, while decreasing latency and hardware vulnerabilities.

This chapter has reviewed CAN-BUS technology including its invention, early applications, fundamentals, and standards development. Early applications of CAN-BUS came from European car manufacturers, which incorporated electronic control units for engine care management. The development of standards to allow consistent communication methods within CAN-BUS systems, such as ISO 11898, SAE J1939 and ISO 11783, were important for allowing serial networks to be applied within multiple vehicle types and industries. Modern day uses, alternative connectivity and networks, and potential future applications have also been examined. Controller area networks are responsible for the transmission, logging, and analysis of engine and machine system data currently used by vehicle manufacturers. Understanding CAN-BUS communication protocols provides insight into the advantages, uses, and future evolutions of distributed control networks.

CAN-BUS technology fundamentals, such as physical and data message structures, components, error handling, and message channel support are useful in understanding the strengths and limitations of CAN systems. Through the use of high and low speed CAN-BUS configurations, arbitration codes, and broadcast style communication, CAN-BUS can efficiently and reliably transfer messages across a vehicle's control system to ensure accurate, real-time data communication. As electronic connectivity has increased the sophistication of off-road vehicle operation management, new applications using CAN with external networks have been an important area of communications advancement within the agricultural sector. The development of converters between CAN data and other wireless data types has been important in keeping CAN-BUS integrated and relevant in the vehicle fleet telematics expansion. More research into wireless CAN may be an important direction for serial network technology going forward.

Specific CAN-BUS applications in ongoing autonomous vehicle development research include component data consolidation, embedded sensors, IoT devices, and machine-to-machine communication strategies. Future technologies that might benefit CAN-BUS technology by their incorporation include local-to-cloud data transmission, autonomous swarm vehicle management, and increased cyber security protocols. Although controller area networks face limitations within both bandwidth and latency, they still function as effective inputs to more advanced vehicle systems and more sophisticated remote networks. The potential of CAN-BUS technologies has clearly not been fully exhausted, and they will continue to play an important role in the advancement of agricultural machinery and farming practices.

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Conflict of interest

The authors declare no conflict of interest.

Author details

Hannah M. Boland, Morgan I. Burgett, Aaron J. Etienne and Robert M. Stwalley III*
Agricultural and Biological Engineering, Purdue University, West Lafayette, Indiana, USA

*Address all correspondence to: rms3@purdue.edu

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