Grains

Engineering Fundamentals of Drying and Storage

Fuji Jian
Digvir S. Jayas

CRC Press
Taylor & Francis Group

Grains

Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com

Grains

Engineering Fundamentals of Drying and Storage

Fuji Jian and Digvir S. Jayas

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

First edition published 2022
by CRC Press
6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL 33487-2742
and by CRC Press
2 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

CRC Press is an imprint of Taylor & Francis Group, LLC

Library of Congress Cataloging-in-Publication Data

Names: Jian, Fuji, author. | Jayas, Digvir S., 1958- author.
Title: Grains : engineering fundamentals of drying and storage / Fuji Jian, Digvir S. Jayas.
Description: First edition. | Boca Raton : CRC Press, 2021. | Includes bibliographical references.
Identifiers: LCCN 2021032664 (print) | LCCN 2021032665 (ebook) | ISBN 9781032013985 (hardback) | ISBN 9781032029993 (paperback) | ISBN 9781003186199 (ebook)
Subjects: LCSH: Grain--Drying. | Grain--Storage.
Classification: LCC SB189.77 .J53 2021 (print) | LCC SB189.77 (ebook) | DDC 633.1/046--dc23
LC record available at https://lccn.loc.gov/2021032664
LC ebook record available at https://lccn.loc.gov/2021032665

ISBN: 978-1-032-01398-5 (hbk)
ISBN: 978-1-032-02999-3 (pbk)
ISBN: 978-1-003-18619-9 (ebk)

DOI: 10.1201/9781003186199

Typeset in Century Old Style Std
by KnowledgeWorks Global Ltd

Contents

Preface

Drying and storage are two significant unit operations in the food industry and are applied to both raw and processed products including cereal grains, oilseeds, legumes, flour, noodle, coffee, and cornstarch. The common characteristic of these materials is that all of them are hygroscopic and contain water. The hygroscopic properties are influenced by their physical properties, which are influenced by their storage environments such as bins, warehouses, bunkers, and temporary storage structures. This book focuses on the storage and drying of bulk products in these storage structures.

On many occasions in our work with the grain storage and drying personnel especially our graduate students and industry contacts, we found a book explaining the fundamental principles of grain storage and drying is needed. Therefore, the primary objective of this book is to help readers understand the fundamental principles of grain storage and drying and develop a well-informed approach to solve grain storage and drying problems. Technologies for grain storage and drying are advanced through research; therefore, literature review and background on each topic has also been included. The book is generally intended for grain storage and drying students, engineers, and scientists. As reflected in the contents which are presented at several levels of depth, this book will serve well readers with different backgrounds and interests. An effort has been made to allow for independent reading of different sections, and to make a large part of this work accessible to a non-mathematical audience.

The authors have combined their experience of teaching grain storage and drying to undergraduate and graduate students in the faculties of Agricultural and Food Sciences and Engineering. Material in the book is

organized into broad topic areas: physical properties (Chapters 1 and 2), grain temperature and moisture (Chapters 2 and 6), water in biomaterials and relationship with its environment (Chapter 3), fundamental principles of aeration, drying, and rewetting (Chapter 4), and mathematical modelling of isotherm, drying, and re-wetting (Chapter 5).

We hope our readers will benefit from the contents of the book for many decades.

Acknowledgements

Humans have stored grains since they started cultivating grains, thus the field of grain storage and drying is mature but research and development in different aspects of storing and drying grains continues to advance with time. There are a huge number of publications in literature. To bring this established field into a single book, we relied heavily on the published articles (listed at the end of each chapter), and gratefully acknowledge the contributions of each researcher and their teams around the globe whose work we have cited. Great care has been given in paraphrasing their works and hope we have succeeded in doing so. We ask for their forgiveness if we have not done it correctly. Even though the published works have been selectively cited based on the relationship to the presented topics, all the published works are critical to the growth of this established but ever-expanding field. We hope our presentation will continue to inspire readers to explore field further. We thank readers for reading whole or parts of the book and we hope with the enhanced understanding of the subject matter you will be designing better systems to manage stored grains safely around the globe and helping feed the growing world population.

Writing of a book requires dedicated time in our daily busy schedules and when focusing on writing, the family gets less attention. We sincerely thank our spouses (Mrs. Suping Yang Jian and Mrs. Manju Jayas) and our children (Annie Jian, Erick Jian, Drs. Rajat Jayas, Ravi Jayas, and Rahul Jayas) for their understanding and support. Dr. Jayas also thanks his grandchildren (Priya Jayas, Isabella Jayas, Rohan Jayas, Gabriel Jayas, and Leon Jayas) for not spending as much time he would like to spend with them. During busy times of writing, we may have not unconsciously completed

some of our assigned duties at work in a timely fashion, and for this we thank our employer, the University of Manitoba, our immediate supervisors, and close working colleagues for their understanding and encouragement.

We acknowledge gratefully the assistance we received from Sonal Motla in copyediting the book, Siobhán Greaney and Ashraf Reza, for spearheading the project through the production process, and Taylor & Francis Group for giving us an opportunity to write this book.

Last but not the least, we thank the readers of the book in whole or in part and hope they will find it useful and will let us know how we could have done it better.

Fuji Jian
Digvir S. Jayas

About the Authors

Dr. Fuji Jian is a professional engineer and associate professor in the Department of Biosystems Engineering at the University of Manitoba. Fuji was educated at the HuaZhong Agricultural University (China), Henan University of Technology (China), University of Greenwich (UK), and University of Manitoba (Canada). Fuji received his Ph.D. at the University of Manitoba in 2003, and excellence of his Ph.D. studies was recognized with the "Governor General's Gold Medal for outstanding graduate studies academic achievement in Canada" and the "CSAE/SCGR 2004 Ph.D. Thesis Award." After working for a grain storage company (OPI System, Calgary, Canada) for 5 years, he returned to academia as an instructor in 2010 and assistant professor in 2015. He is the recipient of the prestigious 2019 John Clark Award of CSBE/SCGAB and 2020 Merit awards in the category of research, scholarly work and creative activities, University of Manitoba. Fuji's research interests are in the area of post-harvest grain quality, stored-product protection, drying and aeration of grains, and sensor development with the sole purpose to enhance food safety and security. He is the leading authors in 85 of more than 100 technical articles in scientific journals, conference proceedings and books. These publications covered: (1) mathematical modelling of grain storage ecosystems; (2) insect biology and ecology inside stored grain bulks; (3) sampling inside grain bins; (4) physical property of stored grain bulks; (5) safe storage of grain and monitoring; (6) insect control and pesticide resistance; (7) grain aeration and drying; (8) sensor development; (9) biomass processing; and (10) particle segregation. Fuji published more than 30 mathematical models and his expertise

in mathematical modelling and grain storage ecosystem has been instrumental in revitalization of grain storage monitoring industry. Drs. Jayas and Jian received the John Ogilvie Research Innovation Award (CSBE/SCGB) in 2021 for their work on "Mathematical models of stored-grain ecosystems for management of stored grain." Fuji has taught Grain Storage/Crop Preservation, Plant and Animal Physiology for Engineers, Unit Operations, Transfer (mass and heat) Phenomena, and Modelling and Simulation of Biological Systems. He is currently supervising/co-supervising more than 10 M.Sc./Ph.D. students.

Distinguished Professor Dr. Digvir S. Jayas was educated at the G.B. Pant University of Agriculture and Technology in Pantnagar, India; the University of Manitoba; and the University of Saskatchewan. Since 2011, he is serving as Vice-President (Research and International) at the University of Manitoba. Before assuming the position of Vice-President (Research and International), he was Vice-President (Research) for two years, and Associate Vice-President (Research) for eight years. Prior to this, he was Associate Dean (Research) in the Faculty of Agricultural and Food Sciences, Head of the Department of Biosystems Engineering, and Interim Director of the Richardson Centre for Functional Foods and Nutraceuticals. For a year, he has served as Interim President of Natural Sciences and Engineering Council of Canada (NSERC). He is a Registered Professional Engineer and a Registered Professional Agrologist. Dr. Jayas is a former Tier I (Senior) Canada Research Chair in Stored-Grain Ecosystems. He conducts research related to drying, handling and storing of grains and oilseeds and digital image processing for grading and processing operations in the Agri-Food industry. He has collaborated with researchers in several countries and has had significant impact on the development of efficient grain storage, handling and drying systems in Canada, China, India, Ukraine and the United States. He has authored or co-authored over 950 technical articles in scientific journals, conference proceedings and books dealing with issues of storing, drying, handling and quality monitoring of grains. Dr. Jayas has received awards in recognition of his research and professional contributions from the Agriculture Institute of Canada, Applied Zoologists Research Association (India), American Society of Agricultural and Biological Engineers (ASABE), Canadian Institute of Food Science and Technology, Canadian Academy of Engineering, Canadian Society for Bioengineering, Engineers Canada (formerly Canadian Council of Professional Engineers), Engineers and Geoscientists Manitoba (formerly Association of Professional Engineers and Geoscientists of Manitoba), Engineering Institute of Canada, Indian Society of Agricultural Engineers, Manitoba Institute of Agrologists, National Academy of Agricultural Sciences (India), National Academy of Sciences (India), and Sigma Xi. He was the recipient of the 2017 Sukup Global Food Security Award from

ASABE, and the 2008 Brockhouse Canada Prize from NSERC. In 2009, he was inducted as a Fellow of the Royal Society of Canada and in 2018, he was appointed as an Officer of the Order of Canada. Dr. Jayas serves on the boards or committees of many organizations including: ArcticNet, Cancer Care Manitoba Projects Grants and Awards Committee, Churchill Marine Observatory (CMO), Centre for Innovative Sensing of Structures (SIMTReC), Genome Prairie, GlycoNet, Manitoba Centre for Health Policy, National Coordinating Centre for Infectious Diseases (NCCID), North Forge Technology Exchange, NSERC Council, Oceans Research in Canada Alliance Council, Research Manitoba, Research Institute of Oncology and Hematology, RITHIM Steering Committee, and TRIUMF. He has served as the President of the Agriculture Institute of Canada, the Canadian Institute of Food Science and Technology, the Canadian Society for Bioengineering, Engineers Canada, Engineers and Geoscientists Manitoba, and the Manitoba Institute of Agrologists. He currently chairs NSERC Council and the board of directors of TRIUMF and RESOLVE, a prairie research network on family violence. He also chairs the Smartpark (University's Research and Technology park) Advisory Committee.

Taylor & Francis
Taylor & Francis Group
http://taylorandfrancis.com

Chapter 1

Physical Properties of Bulk Grain

Introduction

Granular materials or "bulk solids" are any material composed of many individual solid particles, irrespective of particle size. Crop grain kernels are bulk solids and have to be transported, conveyed, handled, stored, and processed. Thus, characterization of bulk solids regarding their physical properties at static and dynamic conditions plays an important role for product development, optimization, and operation in cleaning, grading, drying, handling, and processing of the crop grains. This chapter mainly discuss the physical properties of bulk of grain kernels.

1.1 Density and Porosity

1.1.1 Density

1.1.1.1 True and Bulk Density

Density of porous grain bulks could be expressed either as true density or bulk density of the grain bulk. The true density of the grain bulk is the weight mass of the grain kernels over the volume occupied by the grain kernels and not including the volume of pore spaces among the kernels in the grain bulk. The true density is also termed as kernel density, which is

DOI: 10.1201/9781003186199-1

similar to the particle density used in the mechanical science. Kernel density is also termed as absolute density or real density.

$$\rho_k = \frac{m}{V_k} \tag{1.1}$$

where ρ_k is the kernel density (kg/m^3), m is the mass (kg), and V_k is the volume occupied by the kernels (m^3). The measured volume includes the volume of the closed pores inside each kernel, but not the externally connected pores among kernels. True densities of cereal grains and oilseeds are in the range of 1110–1450 kg/m^3, while true density of some seeds with large portion of fibre hull (such as sunflower seeds) is less than 1000 kg/m^3 (Table 1.1). Therefore, cereal grain seeds or kernels will sink into pure water because its true density is higher than water (1000 kg/m^3).

Bulk density of grain bulk is mass of grain divided by volume occupied by grain including intergranular space typically filled with air. Bulk density of the porous grain bulk can be changed by packing with force or through vibrations but true density is not affected by packing. Bulk density of the porous grain bulk can be calculated as:

$$\rho_b = \frac{m}{V_b} \tag{1.2}$$

where ρ_b is the bulk density (kg/m^3), and V_b is the volume occupied by the grain bulk (m^3). The volume (V_b) includes the volume of the intergranular air among the grain kernels and the volume occupied by the kernels in the bulk grain. This means that the volume in the bulk density calculation includes both externally connected pores among the kernels and closed pores inside each kernel. Bulk densities of crop grains are in the range of 430–900 kg/m^3 and seeds with high oil content such as canola, hemp, and sunflower usually have a lower bulk density (Table 1.1). When the porosity of grain bulks is reduced, the bulk density of some seeds can be higher than 1000 kg/m^3. Carmen (1996) reported the bulk density of lentil was 935–1190 kg/m^3 at porosity of 27–32%, while Irvine et al. (1992) reported 783–825 kg/m^3 at porosity of 40–43% (Table 1.1).

1.1.1.2 Bulk Density Measurement

Even though different researchers use different methods to measure the bulk density, the main measurement principle is the same, which is to measure the mass of the grain kernels in a specified container with a determined volume. The main differences among different methods are the filling method of the tested grain bulk, removing or retaining dockage and foreign materials, and the temperature of the grain. These different

Table 1.1 Bulk and True Densities and Porosity of Seeds of Cereal Grains, Pulses (Legumes), Oilseeds and Speciality Crops

Crop	*MC (%)*[a]	ρ_b *(kg/m³)*[b]	ρ_k *(kg/m³)*[c]	ε *(%)*[d]	*Reference*
Barley	12.7–16.4	649–664	1346–1372	44–47	Muir and Sinha (1988)
Caper	5.7–14.1	438–399	678–806	41–46	Dursun and Dursun (2005)
Canola[e]	8.1	664–687	1093–1129	33–34	Muir and Sinha (1988)
Corn	4.7–22.0	649–710	1250–1325	43–51	Seifi and Alimardani (2010)
Corn (sweet)	8.4–14.6	698–765	1274–1315	42–43	Karababa and Coskuner (2007)
Dry bean[f]	12.0–18.0	789–826	1385–1434	42–43	Senthilkumar et al. (2018)
Dry bean[g]	12.0–18.0	814–827	1416–1443	42–43	Senthilkumar et al. (2018)
Durum	12.7–16.4	709–744	1372–1377	41–42	Muir and Sinha (1988)
Durum[h]	9.3–41.5	675–711	1241–1333	46–47	Al-Mahasneh and Rababah (2007)
Faba bean	12.6–21.9	761–815	1373–1393	42–45	Irvine et al. (1992)
Flaxseed	7.0–15.1	574–624	1143–1148	45–50	Irvine et al. (1992)
Hemp	9.0–15.0	466–470	1110–1135	55–59	Jian et al. (2018)
Lentil	11.4–18.0	783–825	1392–1409	40–43	Irvine et al. (1992)
Lentil	6.1–24.6	935–1190	1288–1750	27–32	Carmen (1996)
Linseed	7.6–18.2	545–691	1010–1020	32–47	Selvi et al. (2006)
Oats	12.7–16.4	537–555	1315–1329	52–54	Muir and Sinha (1988)
Okra	7.5–46.7	558–592	986–1107	43–46	Sahoo and Srivastava (2002)
Pigeon pea	5.9–22.0	745–806	1251–1305	38–40	Shepherd and Bhardwaj (1986)
Pumpkin kernel	4.0–27.5	481–554	1080–1143	52–56	Joshi et al. (1993)
Red kidney bean	9.8–12.8	582–661	1234–1393	46–58	Isik and Unal (2007)

(*Continued*)

Table 1.1 Bulk and True Densities and Porosity of Seeds of Cereal Grains, Pulses (Legumes), Oilseeds and Speciality Crops (*Continued*)

Crop	*MC (%)*[a]	ρ_b *(kg/m³)*[b]	ρ_k *(kg/m³)*[c]	ε *(%)*[d]	*Reference*
Rough rice[i]	10.0	471–554	1126–1300	53–63	Varnamkhasti et al. (2008)
Soybean	8.0–24.0	630–720	1250–1149	37–45	Kashaninejad et al. (2008)
Soybean	8.0–20.0	708–735	1124–1216	37–40	Deshpande et al. (1993)
Sorghum	12.0–18.0	757–868	1136–1160	33–36	Mwithiga and Sifuna (2006)
Sunflower[j]	3.8–16.7	434–462	706–765	34–43	Gupta and Das (1997)
Sunflower[k]	3.8–16.7	574–628	1050–1250	45–50	Gupta and Das (1997)
Vetch	9.6–17.1	826–861	1286–1370	33–40	Yelcin and Ozarslan (2004)
Wheat[l]	12.7–16.4	725–763	1370–1384	39–40	Muir and Sinha (1988)
Wheat[m]	9.2–11.1	721–749	1343–1491	46–48	Markowski et al. (2013)

[a] Moisture content (wb, %).
[b] Bulk density or test weight measured using Canadian Grain Commission method, or a similar method.
[c] True (kernel or particle) density.
[d] Porosity.
[e] Canola or rapeseed.
[f] Black bean (*Phaseolus vulgaris* L.).
[g] White bean (*Phaseolus vulgaris* L.).
[h] Un-matured durum (green wheat).
[i] Paddy.
[j] Sunflower seed.
[k] Sunflower kernel (without hull).
[l] Three cultivars of hard red spring wheat.
[m] Four cultivars of winter wheat.

measurement methods result in different bulk densities of the same grain variety (cultivar). To avoid this inconsistency, measurement of bulk density in different countries is standardized and termed with different names. Canada and the USA standardize it as Test Weight, but use different test kits. Also, the temperature of the grain should be recorded when the bulk

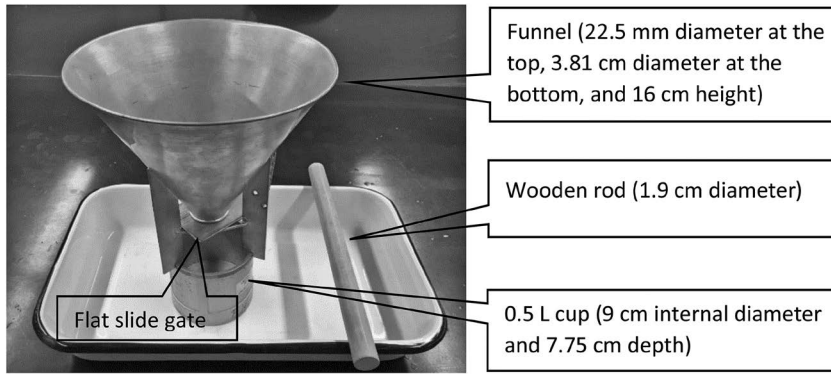


Figure 1.1 Test weight kit specified by the Canadian Grain Commission. The white tray to capture spilled or excess grain from levelling is not included in the kit.

density is measured because temperature slightly influences the bulk density (Jian et al. 2013).

The test weight, specified by the Canadian Grain Commission, is measured by using a specified kit after dockage inside the grain bulk is removed. There is a specified procedure to remove the dockage before the Test Weight is determined (Canadian Grain Commission 2018). The kit includes a 0.5 L cup, wooden rod, and funnel with a flat slide gate at the bottom of the funnel (Fig. 1.1). After the funnel is placed on the top of the 0.5 L cup, the flat slide gate is located 4.41 cm above the cup. The grain to be tested is loaded into the funnel. Then the flat slide gate is opened, the grain drops into the cup, fills it and flows over the sides. The grain at the top of the cup is stroked off with the wooden rod in three zig-zag motions at an angle of 45° and the remaining mass inside the cup is weight. The measured test weight is expressed as kilograms per hectolitre (kg/hL), kilograms per 100 L of volume, or grams per half-litre (g/0.5L), which may commonly be referred to as "bushel weight" and expressed as pounds per bushel (lb/bu), or called "Avery" lb/bu. The "Avery" bushel weight is based on the British "Imperial" bushel volume and one bushel is 36.369 L. One Avery bushel weight in Canadian system is 12.472 kg/m^3. The Canadian Grain Commission recommends the following equation to convert the measured mass in the 0.5 L cup to mass per hectolitre:

$$Y = \frac{1.93736m + 46.4962}{10} \text{ for wheat, oats, barley, rye, and flax} \quad (1.3a)$$

$$Y = \frac{1.91816m + 35.35844}{10} \text{ for rapeseed, caola, and mustard} \quad (1.3b)$$

where Y is the test weight (kg/hL), and m is the mass of grain in the 0.5 L cup (g). The test weight in the USA grading system is measured on the

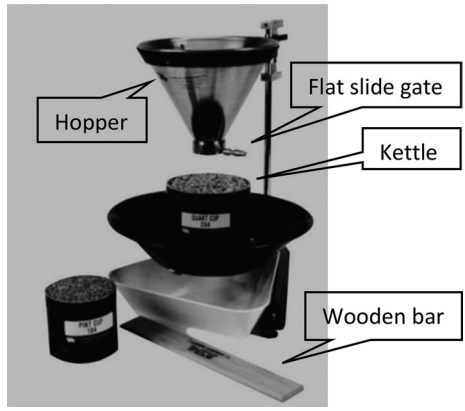


Figure 1.2 Test weight kit approved by the United States Department of Agriculture (USDA).

sample as a whole or after the removal of dockage. A test kit (Fig. 1.2) is approved by the Federal Grain Inspection Service (FGIS), United States Department of Agriculture (USDA). The kit and measurement procedure is similar to the Canadian grading system except the size of the funnel (hopper) and the cup (a quart kettle). The distance between the hopper's base and the top of the kettle is 2 in. The USA grading system uses a wooden striker bar in three zig-zag motions to remove the extra grain from the top of the kettle. Weight of grain in the kettle is measured in pounds and this value is multiplied by 32 (the number of quarts in a volume or Winchester bushel) to obtain the grain test weight in units of pounds per bushel, which is also called pounds per bushel "Winchester" (lb/bu W). The Winchester bushel weight is based on the US bushel volume and one bushel is 35.239 L. One bushel weight in the USA system is 12.872 kg/m^3. Therefore, a bushel of wheat in Canadian system is not equal to a bushel of wheat in the US system. This bushel is not the same as that used to define the weight bushel of crop in the US system. A "weight" bushel of corn is exactly 56 pounds, a soybean bushel is 60 pounds and a wheat bushel is 60 pounds, regardless of the test weight.

1.1.1.3 Physical Properties Influencing Bulk Density

Bulk density is influenced by many factors including grain type, cultivar, dockage and foreign materials in the bulk grain, moisture content, temperature, method of filling (height of fall, flow rate, and vibration), and compaction effect inside the grain bulk because these factors influence the shape and sizes of pores among kernels.

For clean grain, the grain moisture content is the most important factor influencing the bulk density. Bulk density of grain linearly or quadratically decreases with the increase of moisture content in certain range of the grain moisture content and also decreases when grain is over dried (Sun et al. 2014; Jian et al. 2018; Senthilkumar et al. 2018). Compared with wheat, the bulk density of canola is affected less by moisture content, increasing from 690 kg/m^3 at 14.5% moisture content to 700 kg/m^3 at 6.5% moisture content (Jayas et al. 1989). Whereas the bulk density of hard red winter wheat increased from 650 kg/m^3 at 24% moisture content to 770 kg/m^3 as moisture content decreased to 11% (Nelson 1980).

Compared with the moisture content, temperature has a small influence on the bulk density. However, this influence will increase if the grain has a higher than the recommended safe storage moisture content and temperature is lower than 0°C (Jian et al. 2013). Bulk density of canola had a parabolic relationship with temperature and moisture content of the canola seeds.

Bulk densities increase with the applied pressure. Soybean bulk densities varied with pressure in a manner similar to creep behaviour in other agricultural materials (Milani et al. 2000). Thompson and Ross (1983) reported the change in bulk density at 7 and 35 kPa was caused by the rearrangement and the packing characteristics of grain in mass. The change in bulk density at 35–172 kPa was mainly a function of the elasticity and deformational capabilities of the grain kernels. As pressure increases, the voids diminish and the change of bulk density per unit pressure increase decreases. Therefore, the bulk densities approximately linearly increase with pressure above 14 kPa. The bulk density changes of wheat caused by elastic behaviour of individual kernels are higher at high pressures (34–172 kPa) and moisture contents (16–24%). At higher pressures, the increase of bulk density is due to individual kernels deformation (Milani et al. 2000) because grain kernels are more elastic at higher moisture content of soybeans (10.5–20%) at 0–55.2 kPa.

Increase of dockage percentages usually decreases the bulk density (Bian and Subramanyam 2015) because the dockage may include broken kernels, weed seeds, stems (chaff), and leaves. These dockage materials usually have a low true density and irregular shapes, which usually is not the same as the grain kernels, and these different shapes and sizes increase the porosity of the grain bulk. Highly elongated particles with random orientations have 5% more voids than circular particles, while very elongated particles have in 7% lower of bulk density than circular particles (Cleary and Sawley 2002). Vibration can decrease the bulk volume and hence the increase of the bulk density. Cleary and Sawley (2002) found non-circular particles reach to higher bulk densities after vibration. Dockage with smaller dimensions than the grain kernels may increase the bulk density because the dockage will fill in the pore spaces among grain kernels. The

bulk density of hemp seeds with moisture content from 9 to 15% significantly increased when 5–15% dockage (more than 45% of the dockage was smaller than the hemp seed kernels) is mixed with the seeds (Jian et al. 2018). Bulk density of corn mixed with fines increases (McNeill et al. 2004). However, hand shelled corn having little mechanical damage can have a higher bulk density than the corn threshed in a combine due to a higher broken ratio. Therefore, chaff and fines usually have more influence on the bulk density than moisture content and temperature, and this influence depends on the components of the chaff and fines.

Bulk density is a good indicator of grain quality and higher bulk density normally means higher quality because bulk density decrease as grain deteriorates (Jian et al. 2012). The bulk density of canola seeds with 5.5–15.5% moisture contents decreased about 3% after 60 days storage at 30°C (Jian et al. 2012). Compaction will increase the bulk density, and newly harvested canola with moisture content from 5.5% to 15.5% has a compaction ratio of 3.6–7.7%, while the same seeds after 60 days storage period at 30°C have a compaction ratio of 3.5–10% (Jian et al. 2013). Compressibility index (C_I) and Hausner ratio (H_R) can be calculated as:

$$C_I = \frac{\rho_c - \rho_b}{\rho_c} \tag{1.4a}$$

$$H_R = \frac{\rho_c}{\rho_b} \tag{1.4b}$$

where C_I is the compressibility index, H_R is the Hausner ratio, ρ_b is the bulk density (kg/m^3), and ρ_C is the compacted density (kg/m^3). Bulk density in stored grain bin can be estimated when grain mass loaded in the bin is known and volume occupied by grain can be calculated. Bulk densities in a grain bin can be different from the lab measured bulk density. The density in a bin also varies with height of fall and method of filling, and the location of the grain inside the bin. The bulk density of wheat filled with a spout is 3–5% higher than the test weight (Stephens and Foster 1976). Chang et al. (1981) observed an increase in the bulk density from 5 to 9% for wheat, 6 to 10% for corn, and 11 to 12.5% for sorghum when spreaders were used. Bulk density of grain filled by spout has a wider variation than that filled by spreader (Jayas et al. 1989). During grain drying, there will be a reduction in volume due to shrinkage, which will result in the increase of bulk density. Bowden et al. (1983) reported a 10% reduction in grain volume due to drying of barley from 22 to 14% moisture content. Variation of bulk density in a bin results in uneven distribution of porosity. Mathematical models are developed to estimate the bulk density inside bins (Milani et al. 2000; Bhadra et al. 2015; Bhadra et al. 2018). The developed model usually considers the effect of moisture content, grain type, test weight, bin geometry, and bin wall material.

1.1.1.4 True (Kernel) Density Measurement

There are two general methods used to measure the true density: liquid displacement or gas displacement. The most used liquids are toluene, alcohol, tetrachloroethylene, oil, and mercury. In liquid displacement method, the weighed kernels are directly dropped in the liquid, and the volume of the displaced liquid is assumed as the volume of the tested kernels. Selection of the liquid depends on the requirement of measurement accuracy and the dissolving property of the kernels in the liquid. It is required the liquid will not penetrate into the grain kernels and the chemicals inside the kernels will also not dissolve into the liquid. This requires that the used liquids should have a low surface tension and be absorbed very slowly by the grain seeds. Coating of kernels with films or paints may be required to prevent liquid absorption. The surface tension of most liquids, like water or mercury, poses a problem for the determination of void space volumes for most grain and seed kernels (Chang 1988). Even though toluene displacement method has a low accuracy, it is used by researchers in the literature because it is simple to operate. If some chemical compounds inside grain kernels can be dissolved into toluene, the accuracy of toluene method also decreases. For a quick estimation of the true density, water can be used instead of toluene. The volume of the weighed sample inside the water should be measured immediately after the sample is dropped in the water (Jian et al. 2018).

The gas pycnometer is specially designed for the measurement of true density by employing Archimedes' principle of fluid (gas) displacement and the technique of ideal gas expansion. The gas pycnometer method usually has a higher accuracy than the liquid displacement method because helium used in the pycnometer can penetrate faster in every surface and flaw down to about 1 Å, thereby enabling the measurement of volumes with a high accuracy (can go up to 0.02% of the sample volume). The measurement of true density by helium displacement often can reveal the presence of impurities and occluded pores which cannot be determined by other methods because it (1) can rapidly penetrate into small pores due to its small molecules; (2) is not adsorbed due to its inert property; (3) can be considered as an ideal gas for pressures and temperatures usually employed in the test; and (4) provides a useful means for determining porosity of low permeability grain due to its higher diffusivity than other gases (CO_2, N_2) or liquid (such as water). High concentration nitrogen can also be used to replace helium with a slight lower accuracy. If there are pores in which the gas cannot penetrate, the measured pore volume will be less than the true pore volume.

The gas pycnometer is developed based on the principle of porosity tank method (Figura and Teixeira 2007). The gas can be helium, nitrogen, or air (accuracy is lower when air is used). The porosity tank method includes two tanks with the same volume, three valves, and a manometer for the pressure measurement (Fig. 1.3). After the sample is loaded inside

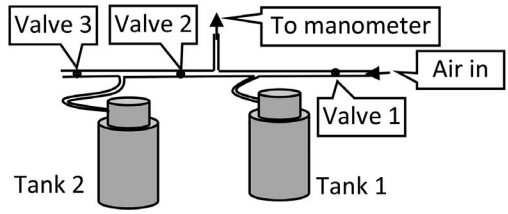


Figure 1.3 Schematic of porosity measurement set up (porosity tank method). (Adapted from Figura and Teixeira, 2007).

tank 2 and the initial pressure (P_1) in the system is measured, the valve 2 and valve 3 are closed. Then compressed gas is introduced in tank 1. After valve 1 is closed and the pressure inside the tank 1 is measured (P_2), valve 2 is opened and the pressure inside the system is measured again (P_3) by using the manometer. Based on the idea gas law, the gas mass inside tank 1 and 2 before valve 2 is opened is:

$$m_a = \frac{P_1(V_2 - V_s)}{RT_1} + \frac{P_2 V_1}{RT_2} \tag{1.5a}$$

After the valve 2 is opened, the same amount of gas mass is distributed in tank 1 and 2, and can be calculated as:

$$m_a = \frac{P_3(V_2 - V_s)}{RT_3} + \frac{P_3 V_1}{RT_3} \tag{1.5b}$$

where m_a is the mass of the gas (kg), R is the specific gas constant ($J \cdot kg^{-1} \cdot k^{-1}$), T_1, T_2, T_3 are the temperatures measured before and after the compressed gas is introduced, and after tank 1 and tank 2 reach equilibrium, respectively (K); P_1, P_2, P_3 are the pressures measured in tank 1 at the very beginning, in tank 2 after the compressed air is introduced, and in both tank 1 and tank 2 after valve 2 is opened, respectively (Pa); and V_1, V_2, V_s are the volumes of tank 1, tank 2, and the sample, respectively (m^3).

The volume of the sample is:

$$V_s = V_2 - \frac{\frac{P_2}{T_2} - \frac{P_3}{T_3}}{\frac{P_3}{T_3} - \frac{P_1}{T_1}} V_1 \tag{1.5c}$$

If $V_1 = V_2$, $T_1 = T_2 = T_3$, then

$$V_s = V_2 \left(1 - \frac{P_2 - P_3}{P_3 - P_1} \right) \tag{1.5d}$$

If the tank 2 is filled entirely with the sample, then the porosity of the sample (ε) is:

$$\varepsilon = \frac{P_2 - P_3}{P_3 - P_1} \tag{1.5e}$$

The true density (kernel density) can be calculated as:

$$\rho_k = \frac{m}{V_s} = \frac{m}{V_2\left(1 - \frac{P_2 - P_3}{P_3 - P_1}\right)} \tag{1.5f}$$

where m is the mass of the sample.

1.1.1.5 Physical Factors Influencing True Density

Kernel density is mostly affected by crop types, classes within a type and cultivars within a class, growing conditions, harvesting methods, and the moisture content of the grain kernels (Table 1.1). The growing conditions determine the plumpness of the kernels and harvest method determines the mechanical damage to kernels. It is usually assumed kernels are incompressible inside stored bins. Therefore, the kernel density will not be influenced by methods of filling and compaction effect inside the grain bins. True density of cereal grain kernels is linearly decreased with increase of moisture content (Isik and Unal 2007; Jian et al. 2012; Sun et al. 2014; Senthilkumar et al. 2018) because density of water is usually less than that of the dry matter of the grain kernels. Since oils are lighter than water, seeds with high oil content also have low kernel density. However, for the grain kernels like hemp seeds, which has gaps between the seed coat and cotyledon inside the kernel, the true density linearly or quadratically increases with the moisture content increase. The reason is that seed coat may not enlarge much when seed moisture content is increased, and the water is absorbed by the cotyledon and the expanded cotyledon replaces the air space. The gaps between the cotyledon and coats become smaller or disappear after the cotyledon expansion (Jian et al. 2018). The seed coat of the hemp seeds is harder than pulses and cereal grains.

1.1.2 Porosity

1.1.2.1 Porosity (ϵ) and Measurement

Porosity of a grain bulk is the ratio of the volume of intergranular pores to the total volume occupied by the grain bulk. Porosity can be reported as percentage or decimal from 0 to 1.

There are many methods to determine the porosity, pore size, and pore structure of any porous material such as rock, soil, and drug in different fields. The most used methods are gas or water vapour sorption, pore saturation (gas or liquid replacement), pycnometer (gas expansion), mercury intrusion, microscopy, and imaging technique (Anovitz and Cole 2015). Image processing method such as QEMSCAN imaging, nuclear magnetic resonance, CT scan, and scattering methods can calculate the porosity by determining the microscopic view of a random section of the porous medium in two or three dimensions. Helium porosimetry using pycnometer is an easy and established technique that can measure only open pores. Due to the limitation of some methods, the most used methods to determine the porosity of grain bulks are pore saturation (gas or liquid replacement) and pycnometer (gas expansion) methods. Only a few publications using imaging technique (Neethirajan et al. 2008) are available. These methods are also used to measure the true density of grain bulks.

The concept of effective porosity has been used in the study of airflow resistance, which is defined as the ratio of the interconnected (effective) pores to the total volume of the porous material. The effective or open pore is the pore that allows fluids or volatiles to flow through it, while the ineffective or closed pore is the non-conducting pore space, includes the occluded pores and the dead-end pores. Effective porosity is most commonly considered in grain industry because it is related to airflow resistance and distribution. Even though pycnometer method cannot be used to directly measure the effective porosity, the effective porosity should be similar to the porosity determined by helium – pycnometer method because it only measures the open pores and there are negligible disconnected pores in grain bulk (Neethirajan et al. 2006).

Porosity (ε) is usually calculated from bulk and true density in literature as:

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_k}\right) \times 100\% \tag{1.6}$$

It should be noted that the porosity does not give any information concerning pore sizes, their distribution, and their degree of connectivity. Thus, the porosity of porous materials consisting of mono-sized spheres range from 0.26 to 0.48 (Woodcock and Mason 1987). The crop grains have about 40% porosity and it ranges between 35 and 55% even though different grain kernels have different kernel sizes and shapes (Table 1.1).

1.1.2.2 Physical Properties Influencing Porosity

Any factor influencing bulk density of a grain bulk affects the porosity. These factors include moisture content, temperature, percentages

of dockage, and method of filling. For most crops (such as wheat, corn, canola), porosity linearly decreases with the increase of bulk density (Chung and Converse 1971). Porosity of crop grain usually increases with the increase of moisture content (Muir and Sinha 1988) because increased size of the grain kernels with the increase of moisture content will enlarge the pore size among the grain kernels. Porosity of sweet corn seeds increase from 57.5% to 61.3% with the increase of moisture content from 11.5 to 19.7% (Coskun et al. 2006). Porosity is higher at higher moisture content of white wheat, red wheat, and corn but lower at higher moisture content of soybeans (Molenda et al. 2005). Porosity of grain seeds with hard seed coat may not be affected by moisture content because the size of the grain kernels may not change much as the grain moisture content changes. Therefore, the change of porosity with change of moisture content depends on grain types. Different sizes of dockage have different effect on the porosity. If the dockage can fill in the pore spaces among the grain kernels, porosity will be decreased; otherwise, it will increase (Jian et al. 2018). Grain inside a storage bin is usually loaded from certain heights. This results in compact forces on the grain bulks during loading and storage. Bulk density inside storage bins is not uniformly distributed. This variation results in the variation of porosity inside grain bulk which would cause non-uninform distribution of airflow resistance (Jian et al. 2019).

1.2 Geometrical Properties of Grain Kernels

1.2.1 Dimensions (Size) and Measurement

Dimensions (size) of grain kernels are usually measured along three mutually perpendicular axes because measurements in more than three dimensions are usually difficult and not necessary (Jian et al. 2018). The three mutually perpendicular axes account for some 93% of variation in volume. Of this total percentage, the intermediate axis contributes only 4% to volume prediction (Mohsenin 1986). The three mutually perpendicular axes are termed as major (principal), medium, and minor axes (diameter), which corresponds to length, width, and thickness (depth) of the kernel, respectively.

The length, width, and thickness can be directly measured by using a calliper. After the kernel freely rests on a levelled flat surface, the longest dimension in the horizontal plan is the length, the shortest is the width, and the longest dimension in the vertical plane is the thickness (Fig. 1.4). Dimension (size) of grain kernels can also be determined using the projected area method produced by a light source located in different

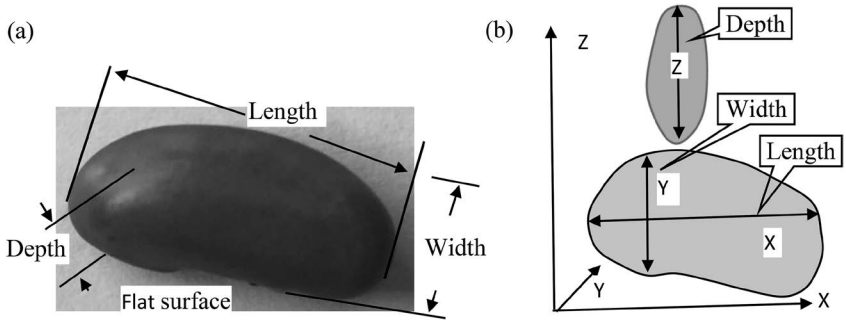


Figure 1.4 (a) Representation of length, width, and depth of a typical red kidney bean rested on a flat surface (Jian and Jayas 2018) and (b) two maximum project areas generated by light sources on the X-Y and Y-Z planes.

angles or a shadowgraph tracing the area on a light sensitive or ordinary graph paper. Two maximum project areas can be generated by using a light source at the top (generating the projected area in the X-Y plan, Fig. 1.4) and side (generating the projected area in the X- or Y-Z plan, Fig. 1.4) of the rest kernel, respectively. The major diameter (length) is the longest dimension of the maximum projected area on the X-Y plane (Fig. 1.4). Intermediate diameter (width) is the longest dimension (diameter) on the X-Y plane and in the direction perpendicular to the major length line. Minor diameter (thickness) is the longest dimension on the X- or Y-Z plane (Fig. 1.4).

Indirect methods, such as digital image processing (Senthilkumar et al. 2018) and particle size distribution analysis, are also used to determine the dimension of grain kernels. Particle size distribution analysis determines both size of particles and their status of distribution. Particle size distribution analysis method is most used for powder and dust particles and this method cannot exactly measure the dimension of grain kernels.

After the dimension of grain kernels are measured, the geometric mean, equivalent, and arithmetic diameters can be estimated as (Mohsenin 1986):

$$D_g = (LW\text{Ŧ})^{1/3} \tag{1.7a}$$

$$D_e = \left[L \frac{(W + \text{Ŧ})^2}{4} \right]^{1/3} \tag{1.7b}$$

$$D_a = \frac{L + W + \text{Ŧ}}{3} \tag{1.7c}$$

where D_g, D_e, and D_a are geometric mean diameter (m), equivalent diameter (m), and arithmetic diameter (m), respectively; and L, W, T are the length (m), width (m), and thickness (m), respectively.

1.2.2 Surface Area and Volume

After dimension of grain kernels are measured, surface area can be predicted by using empirical equations (Mohsenin 1970; Deshpande et al. 1993; Avena-Bustillos et al. 1994; Jain and Bal 1997).

$$S = 2\pi L^2 + \pi \frac{W^2}{e} ln \frac{1+e}{1-e} \tag{1.8a}$$

$$S = \pi T^3/2 + \frac{LT}{2e} \sin^{-1} e \tag{1.8b}$$

$$S = 2\pi W^2 + 2\pi \frac{LW}{e} \sin^{-1} e \tag{1.8c}$$

$$e = [1-(T/L)^2]^{1/2} \tag{1.8d}$$

$$S = \frac{\pi \sqrt{WT}\, L^2}{2L - \sqrt{WT}} \tag{1.8e}$$

$$S = \pi D_g^2 \tag{1.8f}$$

$$S = \frac{\pi L L_m}{2}\left(\frac{L_m}{L} + \frac{1}{u} \arcsin U\right), \quad L_m = \frac{W+T}{2}, \quad U = \frac{\sqrt{L^2 - L_m^2}}{L} \tag{1.8g}$$

where S is the surface area (m^2). Surface area can also be directly measured by using light project method or by using an optical planimeter. An external coat of silicon rubber solution or other similar material can be applied to the surface of grain kernels. The surface area can be determined by peeling off the external coat (Jindal et al. 1974). Coating method is mostly used in the literature published before 1980s.

Different researchers suggest different empirical equations to estimate volume (Deshpande et al. 1993; Jain and Bal 1997; Markowski et al. 2013). Most of these empirical equations are developed by using the relationship among volume and dimension of regular shapes such as sphere and ovoid. The most used empirical equations are:

$$V = \frac{4}{3}\pi L W^2 \tag{1.9a}$$

$$V = 0.25[(\pi/6)L(W+Ŧ)^2 \tag{1.9b}$$

$$V = \frac{\pi W Ŧ L^2}{6\left(2L - \sqrt{W Ŧ}\right)} \tag{1.9c}$$

$$V = \frac{\pi L W^2}{6} = \frac{\pi D_g^3}{6} \text{Prolate spheroid (e.g., lemon)} \tag{1.9d}$$

$$V = \frac{\pi L^2 W}{6} = \frac{\pi D_g^3}{6} \text{Oblate spheroid (e.g., grapefruit)} \tag{1.9e}$$

$$V = \pi h\left(r_1^2 + r_1 r_2 + r_2^2\right)/3 \text{ Right circular cone (e.g., carrot)} \tag{1.9f}$$

$$V_k = \frac{\pi D_e^3}{6} \tag{1.9g}$$

$$V = \frac{\pi}{6} L W Ŧ \tag{1.9h}$$

where r_1, r_2, and h are the radii of the base, top, and height of the cone. Volume can also be directly measured by using the liquid displacement method mentioned in the measurement of true density and porosity. These methods cannot provide enough accuracy for a single kernel but can measure the average volume of kernels after a known number of kernels are used. If high accuracy of the volume measurement is required or suitable liquid is not available, gas displacement method or pycnometer is mostly used.

1.2.3 Shape and Shape Factors

Different terms have been used to define the shape of particles. These terms include elongation, lengthiness, flakiness, shape factor, sphericity, roundness, and aspect ratio. Shape of particles can be judged by the measured length, width, and thickness.

1.2.3.1 Elongation, Lengthiness, and Flakiness

$$E_l = \frac{L}{W} \tag{1.10a}$$

$$f = \frac{W}{Ŧ} \tag{1.10b}$$

where E_l is the elongation or lengthiness, and f is the flakiness. Plate-like materials such as leaves and kennels of lentil have large values of f, while needle-like materials such as chaff and kernels of rye have large values of E_l.

1.2.3.2 Shape Factor

Shape factor can be calculated as (Jain and Bal 1997):

$$S_v = V/W^3 \tag{1.11a}$$

$$S_s = \frac{S}{6W^2} \tag{1.11b}$$

$$\lambda = S_v/S_s \tag{1.11c}$$

where λ is the shape factor, S_v is the volume-based shape factor, and S_s is the surface-area-based shape factor. Gorial and O'callaghan (1990) found the volume shape factors for different types of grain lie between 0.27 and 0.49. The term of shape factor has been misused and has different definitions under different applications. When the terminal velocity is measured, the shape factor is termed as the ratio of the geometric mean diameter to the diameter of an equivalent sphere. This definition is the same as one of the definitions of sphericity.

1.2.3.3 Cross Section

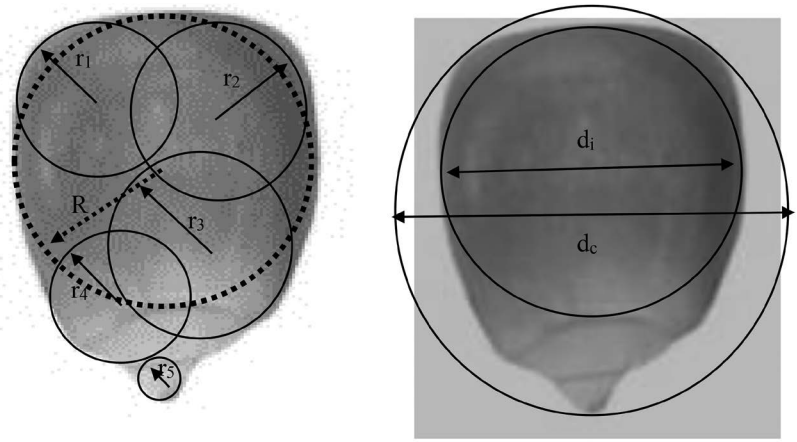
The cross section of a particle is usually the projected cross section when viewed in the direction of the thickness. The diameter of the projected cross section is the diameter of the circle having the same area as this projected cross section.

$$d_p = \left(\frac{4}{\pi}WL\right)^{1/2} \tag{1.12}$$

where d_p is the diameter of the projected cross section (m).

1.2.3.4 Sphericity

Sphericity is defined in three ways: (1) the ratio of the surface area of a sphere, which has the same volume as the kernel, to the actual surface area of the kernel; (2) the ratio of the diameter of a sphere of the same volume as the object to the diameter of the smallest circumscribing sphere; and (3) the ratio of the diameter of largest inscribed sphere to the diameter of the smallest circumscribed sphere (Fig. 1.5). Based on these definitions, the



$$Roundness = \frac{\sum r}{NR} = \frac{r_1 + r_2 + r_3 + r_4 + r_5}{5R} \qquad Sphericity = \frac{d_i}{d_c}$$

Figure 1.5 Conceptual diagrams of roundness described by Wadell (1932) and sphericity described by Curray (1951). The thickness of the corn kernel is larger than 2*R* and less than d_c. *N* = number of spheres, *r* = radius of a sphere, d_i = diameter of the minimum inscribed sphere, and d_c = diameter of the maximum inscribed sphere.

sphericity of a perfect sphere is 1. It is usually difficult to exactly measure the surface area of a kernel. Therefore, sphericity is usually estimated by using the measured dimensions along three mutually perpendicular axes.

$$Ø = \frac{D_g}{L} \tag{1.13a}$$

$$Ø = \frac{D_p}{D} \tag{1.13b}$$

$$Ø = \frac{D_e}{L} \tag{1.13c}$$

$$Ø = \left[\frac{\sqrt{WT}\left(2L - \sqrt{WT}\right)}{L^2} \right]^{1/3} \tag{1.13d}$$

$$Ø = \frac{6\,V_k}{D_e S}, \quad \text{and} \quad S = \pi D_e^2 \tag{1.13e}$$

where D is the diameter of the circle circumscribing the project area (m). Different equations may not necessarily yield the same results. Sphericity of grain kernels is from 0.40 to 0.88 (Table 1.2).

1.2.3.5 Roundness and Aspect Ratio

Roundness (circularity or roundness ratio) is used to measure the smoothness of the particle. Roundness is usually not measured in the grain industry due to the difficulty of its measurement. The most accepted definition is proposed by Wadell (1932) and the definition is the ratio of the average curvature radius of the particle edges and corners to the radius of the maximum inscribed sphere (Fig. 1.5). However, it is difficult to measure the roundness by using this definition because so many spheres inside the kernel should be identified and measured (Fig. 1.5). Different definitions and equations are provided in literature.

$$R_c = \frac{2r_c}{D_L} \text{(Mitchell and Soga 2005)} \tag{1.14a}$$

$$R_c = \frac{r_c}{r_{av}} \text{(Mitchell and Soga 2005)} \tag{1.14b}$$

$$R_c = \frac{4\pi A_P}{P_o^2} \text{(Li et al. 2002)} \tag{1.14c}$$

$$R_c = \frac{A_l}{A_c} \text{(Curray 1951)} \tag{1.14d}$$

$$R_c = \frac{r_{cs}}{r_m} \tag{1.14e}$$

$$R_c = \frac{A_p}{A_c} \times 100 \text{(Mohsenin 1986)} \tag{1.14f}$$

where R_c is the roundness or circularity (decimal or percentage), r_c is the curvature radius of the maximum convex part of the particle (m), D_L is the longest diameter through the most convex part of the particle (m), r_{av} is the mean radius (m), A_p is the particle projected area (m^2), P_o is the overall projection perimeter (m), A_1 is the largest projected area of object in natural rest position (m^2), A_c is the area of smallest circumscribing circle (m^2), r_{cs} is the radius of curvature of the sharpest corner, and r_m is the mean radius of the object.

The aspect ratio (A_R) is calculated as:

$$A_R = \frac{W}{L} \tag{1.15}$$

Table 1.2 Mass of Thousand Kernel, Surface Area, Volume, and Sphericity of Seeds of Cereal Grains, Pulses (Legumes), Oilseeds and Speciality Crops

Crop	*MC (%)*[a]	*MTK (g)*[b]	*Surface (mm^2)*	*Volume (mm^3)*	*Sphericity*	*Reference*
Caper	5.7–14.1	6.6–7.8	15.8–23.1		0.72–0.74	Dursun and Dursun (2005)
Corn	4.7–22.0	271–321	133–160	202–265	0.59–0.62	Seifi and Alimardani (2010)
Corn (sweet)	8.4–14.6	220–268	120–183	94–194	0.63–0.69	Karababa and Coskuner (2007)
Durum[c]	9.3–41.5	32–52	47.1–61.0	29–42	0.69–0.72	Al-Mahasneh and Rababah (2007)
Flaxseed	9.1–15.2	7.2–7.4			0.47–0.48	Bhise et al. (2013)
Hemp	9.0–15.0	12.4–14.1	68.6	13.3 ± 0.6	0.80	Jian et al. (2018)
Kidney bean[d]	8.9–16.4	522–560	278–329		0.73–0.76	Isik and Unal (2007)
Linseed	7.6–18.2	6.0–6.7	15.8–18.6		0.49–0.50	Selvi et al. (2006)
Okra	7.5–46.7	66–130		67–124	0.70–0.77	Sahoo and Srivastava (2002)
Pigeon pea	5.9–22.0	76 ± 1	67.4 ± 2.9	50–65	0.82 ± 0.53	Shepherd and Bhardwaj (1986)
Rough rice	10.0	21.6 ± 0.7	31.8 ± 2.3	20.3 ± 2.3	0.40 ± 1.5	Varnamkhasti et al. (2008)
Soybean	8.0–24.0	145–250	115 – 155		0.81–0.88	Kashaninejad et al. (2008)
Sunflower[e]	5.8	34 ± 1			0.43–0.68	Gupta and Das (1997)
Sunflower[f]	5.8	49 ± 12			0.46–0.67	Gupta and Das (1997)
Vetch	9.6–17.1	55.5–59.0			0.84–0.86	Yelcin and Ozarslan (2004)
Wheat[g]	8.6–9.8	39.7 ± 9.8			56.5 ± 2.8	Gürsoy and Güzel (2010)
Wheat[h]	9.2–11.1	46–52	55.7–67.0	33–42	0.54–0.61	Markowski et al. (2013)

[a] Moisture content (wb, %).
[b] Mass of thousand kernels.
[c] Un-matured durum (green wheat).
[d] Red kidney bean.
[e] Sunflower kernel.
[f] Sunflower seed.
[g] One cultivar (Nurkent) of bread wheat.
[h] Four cultivars of winter wheat.

The roundness and aspect ratio are highly dependent upon the sharpness of the particles and are usually related to their angularity. Krumbein and Sloss (1963) developed the roundness and sphericity chart for visually determining the roundness. A visual measurement of the roundness of grain seeds is not applicable. The following methods that are used in other research areas have also been used by some researchers: fractal analysis, Fourier methods, and image analysis and processing.

The decrease in the roundness or increase in the angularity of the particles will increase the particle interlocking, thereby increasing the angle of repose and decreasing the rolling and flow property of the solid.

1.3 Hardness and Measurement

1.3.1 Hardness

Grain hardness or toughness is most used in the grain processing industry and there is no universally accepted definition. The most used definition of kernel hardness is the resistance of the kernel to penetration of foreign matter or resistance to destruction and breakdown to particles. Hardness is also known as rupture force, is mainly related to plastic deformation of material by indentation. The peak force occurred during the first compression is termed as hardness. Grain hardness has both qualitative and quantitative meaning because hardness is not only related to the kernel firmness, but also related to milling and baking qualities; and for pulses to dehulling and cooking quality. During milling, hardness influences the sieving, energy consumption, fineness of the finished product, and the milling extraction. Milling energy is linearly correlated with kernel hardness (Szabo et al. 2016). Optimal dry milling requires hard kernels, whereas optimal wet milling requires soft kernels.

Hardness is widely used by the wheat industry at the very beginning because different classes of wheat have different hardness (in Canada, there are eight wheat classes and multiple cultivars [varieties] within each class). Studies have been conducted on the effect of hardness on quality in barley (Psota et al. 2007; Turuspekov et al. 2008), triticale (Ramiärez et al. 2003), durum (Anjum and Walker 1991), sorghum (Anglani 1998), millet (Abdelrahman and Hoseney 1984), and maize (Dombrink-Kurtzman and Bietz 1993). Wheat is still the main crop for which its new cultivars are classified on the basis of hardness. The level of hardness often determines the end use of the wheat. Soft, intermediate, and high hardness wheat's are usually used for cookies, bread, and pasta, respectively (Ross 1997; Morris 2002). Soft wheats are more friable, require less energy to mill and produce flours and meals with reduced particle-size distribution, including many

free starch granules. Hard kernels are more difficult to reduce to flour-sized particles, so hard grain flour is coarser, has more broken and damaged starch granules, a larger mean particle size than soft grain flour, but flow more easily. Hard wheat flour has a higher damaged starch produced during the milling process, and damaged starch has a higher water absorption capacity and is more readily hydrolyzed by amylase enzyme.

Hardness is related to the kernel size, kernel density, and vitreousness. Lower density indicates soft kernels. The texture is significantly affected by quantity, quality and the ratio of protein and starch, size of cells and their mutual connections within individual tissues. The interaction between carbohydrates and proteins strongly influences the hardness of endosperm. Texture, i.e., the organization of individual grain components (water-soluble pentosans, lipid content, endosperm, and hulls) determines whether the grain will be hard or soft. Some seeds having high protein content will be hard, while total protein content in some crop seeds do not show significant correlation with kernel hardness (Pasha et al. 2010). Increase in protein can be linked to an increase in vitreousness and hardness (Morris 2002; Morris and Massa 2003). Grain hardness is related to the degree of adhesion between the starch granules and the protein matrix, whereas the endosperm density is affected by the fracture force. Therefore, hardness is a genetic and physicochemical property related to classes regardless its moisture content, even though a grain kernel usually becomes soft with the increase of its moisture content.

The relationship of hardness with the texture, genetic, and physicochemical properties is not completely explicit because many factors influence the hardness. For example, hardness is significantly influenced by classes and farming practice such as different breeding programs and growing locations (Psota et al. 2007). Hardness of wheat and barley is linked to a specific gene family with allelic variation related to variability in hardness and quality. For maize, a number of quantitative trait loci have been linked to a range of hardness measures, including vitreousness. The puroindoline proteins a and b form the molecular basis of wheat grain hardness (Morris 2002). When both a and b are in their "functional" wild state, grain texture is soft, otherwise it is hard if either one of the puroindolines is absent or altered by mutation (Takata et al. 2010). The locus hardness is located on the short arm of the 5D chromosome (Greffeuille et al. 2006).

Two proposed theories explain hardness of wheat: continuity of the protein matrix and physical contact between starch and protein (Moss et al. 1980), and the bond or adhesion between starch and protein (Simmonds 1972; Simmonds et al. 1973). Abdelrahman and Hoseney (1984) found the substances responsible for hardness in those grains are extractable and sensitive to heat. Glenn and Saunders (1990) reported the existence of intracellular space around the starch granules of soft, but not of hard wheat.

This physical discontinuity provides a natural path for shearing forces when the kernel is under pressure, leading to softer material that is more easily reduced in particle size. The degree of adhesion between starch granules and endosperm protein matrix affects hardness (Barlow et al. 1973). Softer wheat has a higher content of amylose bound with lipids and has a lower content of total starch than the harder wheat (Gaines et al. 2000). Classes with softer endosperm texture have larger ratio of 25 μm particles after milling than the ones with harder endosperm (Devaux 1998). These studies further concluded that water-soluble material acts as cement between starch granules and storage protein, across the amyloplast membrane interface. Hardness is also related to lipid and pentosane concentration (Bettge and Morris 2000).

1.3.2 Measurement of Hardness

It is generally recommended that, prior to hardness measurements, samples should be equilibrated to a desired moisture content or a correction factor should be applied (Armstrong et al. 2007). More than 20 methods have been reported and most of these methods are empirical. These methods include measuring compressive strength, impact and shear resistance, resistance to grinding, yield of grits, and starch gelatinization properties (Chandra et al. 2001). The mechanical properties of yield stress, yield strain, and Young's modulus are usually measured to understand the milling properties (Kang et al. 1995). Taylor and Duodu (2009) provide the testing methods for maize, sorghum and other non-wheat cereals. There is no standardized method to measure hardness because each method has advantages and disadvantages and none can provide a complete characterization. Fox and Manley (2009) reviewed these methods. The three most commonly used methods are the particle size index (PSI), near-infrared spectroscopy (NIR), and the Single Kernel Characterization System (SKCS). Some methods such as the SKCS use single kernels and some such as the PSI use bulk grain sample. All those tests respond in different ways to change in grain hardness. A number of factors affect breakage including temperature, moisture, genetics, growing environment, and firmness. Therefore, the measured condition of hardness should be specified. Measurement of grain hardness requires reference materials for instrument standardization. The American Association of Cereal Chemists (AACC) Approved Methods employ reference materials prepared by the US Department of Agriculture Federal Grain Inspection Service (USDA-FGIS). The material is comprised of genetically pure commercial grain lots of five soft and five hard wheat cultivars and is made available through the National Institute of Standards and Technology.

1.3.2.1 Particle Size Index (PSI) Method

This method provides only an indication of the total hardness of a sample and does not provide any information on possible variation within kernels. The grain sample is milled and then fractionated through sieves. The PSI is calculated as:

$$PSI = \frac{m}{\text{Sample mass}} \times 100 \tag{1.16}$$

where m is the mass of the particles passing through a specified sieve (g); and sample mass is the mass of the sample used to conduct the sieving test (g). Researches used different equipment and different number of sieves of different mesh sizes. To test the hardness of the barley, Psota et al. (2007) used a laboratory mill (LM 3303, Perten Instruments, GmbH-Hamburg, Germany) with head number two and 0.075 mm sieve. Ten grams of the milled sample was taken and placed into the Sifter Swing 200 (Mezos, Czech Republic) and sieved for 10 min. Morris and Massa (2003) used Tecator Cemotec 1090 burr mill (Foss-Tecator, Eden Prairie, MN) and AACC 55-30 method to measure the wheat hardness. The ground meal was sifted (Ro-Tap, W.S. Tyler Co., Mentor, OH) using 210 μm opening, 20.3 cm diameter sieves, for 5 min/sample. The weight of the meal recovered from the bottom pan was used to calculate the PSI.

1.3.2.2 Near-Infrared (NIR) Spectroscopy Method

The principle using the level of vitreousness (the proportion of the endosperm that is translucent) as an indirect measure of hardness is that vitreous endosperm has a glassy appearance and is denser than opaque floury endosperm, which contains more airspaces. Endosperm that is translucent against the non-translucent areas shows differences in protein content and composition. Light at particular wavelengths in the near infrared region is absorbed by some bonds such as C-H, O-H, and N-H, which vibrate in proportion to their concentration in the grain. Correlations between vitreousness levels and end-use quality have also been investigated, both in reflectance and transmission modes, and extensively used for indirect measurement of maize kernel hardness. The more vitreous samples are harder than the less vitreous samples. Near-Infrared (NIR) spectroscopy has been used to estimate maize hardness by relating the measured wavelength to the measured values from the Tangential Abrasive Dehulling Device (model 4E-220, Venables Machine Works, Saskatoon, SK) (Wehling et al. 1993), PSI value (De Alencar Figueiredo et al. 2006), Glenn Mill (Glenn Mills Inc, Clifton, NJ) (Armstrong et al.

2007), floaters method (Eyherabide et al. 1996), kernel density (Siska and Hurburgh 1994), and coarse/fine ratio (Robutti 1995) as reference methods. The accuracy and precision of the reference method are critical to the development of any NIR calibration (Hoffman et al. 2010). The use of a single wavelength (860 or 1680 nm) as well as the maximum absorbance/reflectance between 620 and 680 nm have been used to relate to hardness (Robutti 1995). Light Transflectance Meter (LTm) developed by Brewing Research International (Chandra et al. 2001) is used to measure the quantity of light transmitted through a kernel, and low and high LTm values indicate mealy and steely grain texture, respectively. The GrainCheck™ 310 instrument (Hillerød, Denmark) is used to measure the total light reflectance of kernels. The NIR reflectance spectroscopy can be used to measure the baseline shift (BLS) because different grinding-induced particle size will produce different BLS.

1.3.2.3 Single Kernel Characterization System

The SKCS developed by Martin et al. (1993) is most used to measure the single kernel hardness of wheat. The SKCS works by crushing 300 individual grains in a sample between a serrated rotor and a crescent. Both the mean and the standard deviations for the 300 kernels in the sample are reported. The force required to crush individual grains of a sample between two surfaces are measured by taking into account the weight, diameter, and moisture content of the grain. Bean et al. (2006) used a SKCS to evaluate the hardness and moisture content of sorghum and found the SKCS should be suitable for measuring sorghum grain attributes with a lower moisture prediction than the oven method (described in Chapter 3).

1.3.2.4 Methods Measuring the Force to Crush, Shear, or Peal Kernels

Methods measuring resistance to grinding include Brabender hardness test, pressure rod, Tangential Abrasion Dehulling Device (TADD), resistance to pearling, and single-kernel compression. Two steps of Brabender hardness tester measure average energy input and particle size by recording the torque value during grinding (Brabender units). The TADD measures the amount of material removed from kernels when the kernels are abraded for a defined period of time, with higher values indicating softer kernels. Resistance to pearling (Chung et al. 1977) is another method to evaluate the hardness and the milling properties can be studied at various dehulling degrees (Reichert and Youngs 1976). Different researchers used

different equipment and procedures to measure the resistance of kernels when a rod is pressed into the kernels, or compressed under a universal testing machine. Speed reduction and vibration of a mill during grinding can also be used to evaluate the required force.

1.3.2.5 Flour Yield, Particle Size, and Surface Area

These methods include Stenvert method, Roff milling index or milling index, and particle size distribution analysis. Stenvert (1974) method records the time required to fill a 17 mL tube attached to a grinder. A longer time indicate harder kernels. Stenvert method has been modified by some researchers (Mestres et al. 1995) by adding different sieves and computer-controlled data capture to report parameters such as energy usage and time of grinding. The Roff milling index or milling index is calculated from the meal and bran fractions obtained from milling a sample through a roller mill system. A maize sample (preconditioned to 14% moisture) is milled through the roller mill system of three rollers with gaps of 0.3, 0.38, and 0.08 mm. The method can distinguish between maize cultivars with different hardness and identify cultivar and environmental effects on maize hardness. Hard and soft wheats gave different size distribution of the flour and Wu et al. (1990) found mean flour particle size might measure wheat hardness more reliably than PSI.

1.3.2.6 Starch Properties

Starch property methods include the starch gelatinization and diastatic activities. Methods of starch gelatinization properties include ViscoAnalyser (RVA). The RVA is the method that relates biochemical components to hardness of maize. After the sample is ground, the ground material is mixed with water and constantly stirred while the sample is heated to 100°C. The method provides information on starch properties, including paste viscosity, gelatinization temperature, and time (Almeida-Dominguez et al. 1997). The starch damage and diastatic activities are correlated with hardness (Stenvert 1972).

1.4 Shrinkage and Swelling

1.4.1 Shrinkage and Swelling

Shrinkage and swelling are the decrease or increase in volume of grain kernels after grain kernel loses or gains water, respectively (Fig. 1.6). Uniform shrinkage or swelling in all dimensions of kernels are called isotropic