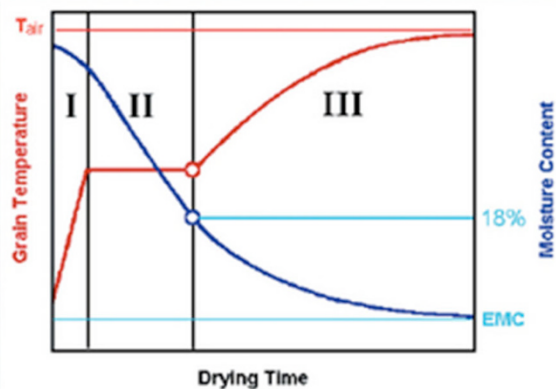


Drying and Storage of Cereal Grains

Second Edition



B. K. Bala

WILEY Blackwell

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B. K. Bala

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WILEY Blackwell

This edition first published 2017
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John Wiley & Sons, Ltd, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom

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Library of Congress Cataloging-in-Publication data applied for:

ISBN: 9781119124238

A catalogue record for this book is available from the British Library.

Set in 10/12pt Warnock by SPi Global, Pondicherry, India

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Foreword to the Second Edition

Drying of cereal grains is an important preservation method prior to storage of the grain. Basic knowledge about fundamentals in drying technology and advanced details about physical and thermal processes during drying and storage of grain is very important not only for students, scientists and engineers in post-harvest technology but also for drying and storage facility managers.

Cereals are globally one of the most important arable crops produced directly for human nutrition. A significantly increasing amount of cereal production worldwide is designated for feeding animals in livestock breeding to produce meat, eggs, milk and so on, finally as an additional nutrition for humans. Higher production of cereals is expected in the future to meet the demand for a sufficient nourishment of humans especially in developing countries. FAO estimates that in the next few decades the production of cereal grains will need to be augmented by one billion tonnes per year to meet the demand for sufficient nutrition of population increasing in the future.

Additionally to these purposes, grain has increasingly grown in the recent decades as a source for bioenergy facilities to produce biofuel and biogas to more and more partly replace mineral oil. For any of these purposes, high quality of traded pure grain and cereal products is requested from manufacturers, wholesalers, retailers and end consumers. Spoiled grain with fungi or pest infection stored in silos or heaps designated even for combustion or biogas production may cause risk of environmental impact or pollution.

High quality of produce is mandatory for assuring nutrition value. It is important to avoid development of microorganisms and fungi and contamination with toxins from it during storage and transport which can cause health risks and may get in conflict with national or international quality standard regulations. Overdried or overheated grain like wheat or barley will result in loss of germination capacity or backing capability.

It is still a severe problem that inappropriate post-harvest conditions during cleaning, sorting, drying, storage, transport, packing and marketing often cause high amount of losses. Deficient or unavailable drying and storing facilities are a problem especially in subtropic or tropic areas. Since the capabilities to increase the productivity of cereals are limited, it is compulsory to reduce their post-harvest losses. Therefore, it is crucial to know well the influences on drying and storing procedures to make the best decisions for installing appropriate equipment and to set the correct parameters for optimal drying and storage of cereals.

Besides post-harvest losses, incorrect operation of drying may cause waste and ineffective consumption of energy which results directly in monetary loss.

Only a profound knowledge about the physical, thermal, (bio)chemical and aeration processes will give the designing engineer and the operator the ability to prevent problems which are associated with drying and storing of grain and to guarantee high quality of the produce and to reduce loss.

The theory in this textbook is comprehensively outlined beginning with principles about drying and physical and thermal basics related to drying and ventilation, continuing with principles of storage and finally with explanations about proper design of drying and storing facilities.

In some chapters the understanding of the theory is supported by modelling examples which are coded in the simple but comprehensive programming language *BASIC*. Enthusiasts in programming can easily find software engineering development packages and tools for programming in *BASIC*. A good number of software packages are available in the Internet for free download. Anyway, the program listings in the chapters of this book can easily be reformatted in other more 'modern' programming languages like *C*, *Pascal*, *Java* and *Python*, which are now becoming more popular among students programming games, but are also well suited for programming numerical methods. A number of well-known and frequently used software packages of so-called computer algebra systems (CAS) with the advantage of built-in graphic capabilities can also be used here excellently for modelling. A number of widespread commercial systems like *MATLAB*, *Maple*, *Mathcad*, *Mathematica* and so on, are frequently used at universities and in industry. But others are open-source packages like *Octave*, *Scilab*, *Maxima* and more. To the student or young scientist, a good number of great possibilities to study and experiment the theory with computer simulation methods using a CAS accessible for free from the Internet are therefore given. With the programming examples in this book, the reader can easily try for themselves, the many variants of different operating conditions for drying and ventilation of grain and then consequently profit from an ease of understanding of the drying processes of cereals.

It should be emphasized here that a profound knowledge of drying and storage processes of grain is important not only for engineers, manufacturers and operators to be able to design and operate properly drying and storage facilities but also for purchasing agents of equipment to be able to make correct and reliable decisions when investing in drying and storage technology.

This book of Professor B. K. Bala about cereal grain drying and storage will excellently give the ability to students, researchers and operators to study the needed fundamental background and detailed theory and practices about appropriate cereal grain drying and storage. The book will also greatly encourage the student to experiment and study the subjects with computer simulation methods.

Prof. Dr.-Ing. Klaus Gottschalk
Leibniz-Institut für Agrartechnik
Potsdam-Bornim e.V.

Foreword to the First Edition

One of the great miracles of nature, the carbon–oxygen cycle, poses two great challenges to mankind:

- How to maximize the amount of solar energy fixed in the photosynthesis phase of the cycle
- How to control the general well-being, the processes of ‘breakdown’, which is nature’s way of recycling the products of photosynthesis

The first challenge is being met by a large corps of husbandry specialists who have selected the plants and proposed methods of husbandry which exploit fully the local environmental potential towards maximizing the yield at harvest. However, even in the most favourable environment we can only expect three harvests in a year. The other challenge is how to reconcile the supply of a perishable commodity which is produced only once, twice or, at most, three times a year with a demand which is relatively rising from 1 day to the next. This is the task of post-harvest technology: how to conserve economically, in nutritious and palatable form, the hard-won fruits from one harvest until the next. Unfortunately, the level of avoidable post-harvest losses is still unacceptably high. This is partly due to the fact that losses accumulate along a long chain of distribution between the producer and consumer and partly because losses due to fungal and mite attacks in stores cause less public outrage than if a crop was left to rot in the field.

There is really only one method of conserving cereal grains between harvest and utilization and that is drying, which is a complicated process. Although drying of cereals has been practised since prehistoric times, it is still not completely understood. It involves both energy and mass transfer in complex biological material, which can be easily damaged. Energy is needed to change water from the liquid phase to the vapour phase. Mass transfer is involved in the migration of water from within the grain to its surface and in the removal of the vapour from the surface of each grain by a stream of air which transports the moisture into the atmosphere. An effective drying operation is one which gets the balance between the two processes of heat and mass transfer just right. In grain drying, the needs to preserve germination, taste and baking quality and to prevent the cracking of the kernels are all constraints on the drying process.

Professor B. K. Bala has written what deserves to be the standard textbook on drying and storage of cereal grains. The approach is comprehensive but accessible. There are good general descriptions of the problems to be tackled, which leads the reader towards an understanding of the broad physical principles that are involved. These principles are then translated into quantitative terms, on which a systematic approach to design is

formulated. There are plenty of worked examples, which help the reader to understand how the principles are applied to a wide range of practical problems. The survey of the background literature is masterly in that it gives recognition to the research workers, who have contributed to the science of drying and storage, while, at the same time, blending the various contributions into a coherent whole.

This book is a major contribution in an important but under-resourced area of post-harvest technology. It unravels the complicated links in the long chain of events between harvest and utilization. It focuses attention on the critical processes at every stage and presents, in an accessible way, design procedures, based on sound scientific principles.

It is a matter of great pride to my colleagues and me, who have worked with Professor Bala in the Newcastle Drying Group, that we have stimulated him to writing such a useful book.

J. R. O'Callaghan
University of Newcastle upon Tyne

Preface

This book has been written primarily for undergraduate and graduate students in agricultural engineering and food engineering. It is the outcome of several years of teaching and research work carried out by the author.

The book covers a very wide spectrum of drying and storage studies which is probably not available in a single book. Chapters 1–8 deal with air and grain moisture equilibria, psychrometry, physical and thermal properties of cereal grains, principles of airflow and detailed analyses of grain drying, and Chapters 9–13 deal with temperature and moisture in grain storages, fungi and insects associated with stored grain, design of grain storages and a comprehensive treatment of modern grain storage systems. Chapters 7 and 10 have been primarily devoted to the application of simulation techniques using digital computers. New sections on net heat of sorption in Chapter 2, finite element modelling of single kernel in Chapter 6, CFD modelling of fluidized bed drying in Chapter 7, exergy analysis and neural network modelling in Chapter 8 and numerical solution of two-dimensional temperature and moisture changes in stored grain have been included in this second edition of the book. A good number of problems have been solved to help understand the relevant theory. At the end of each chapter, unsolved problems have been provided for further practice. The References and Further Reading will help the reader to find detailed information on various topics of his interest.

I have great pleasure in acknowledging what I owe to many persons in writing this book. I am deeply indebted to my teacher Professor J. R. O'Callaghan of the University of Newcastle upon Tyne, United Kingdom, for writing the foreword of the first edition of this book. Also I sincerely express my acknowledgements to Professor, Dr.-Ing. Klaus Gottschalk, Leibniz Institute for Agricultural Engineering, Potsdam, Germany, for writing the foreword of the second edition of this book. At the Jessore University of Science and Technology, I acknowledge the encouragement and assistance received from Professor M. A. Satter, Vice Chancellor, Jessore University of Science and Technology, Jessore, Bangladesh.

B. K. Bala

1

Principles of Drying

1.1 Introduction

Drying is a common activity which has its origin at the dawn of the civilization. It is interesting to note that the knowledge of how to dry and store crops developed enough before how to cultivate crops was discovered. But scientific studies on crop production started before such studies on drying and storage. However, considerable research has been done on drying but surprisingly limited research work on storage has been carried out.

Annual loss of grain from harvesting to consumption is estimated to be 10–25%. The magnitude of these losses varies from country to country. These losses are significantly high in the developing countries because of favourable climates which cause deterioration of stored grains and also because of lack of knowledge and proper facilities for drying and storage. Great efforts are being made to increase crop production, but until now little or no effort is being made to improve drying and storage facilities, especially in developing countries. Most developing countries are facing acute shortage of food and they need food, not production statistics. The post-harvest loss is proportional to production and increases with increased production. A programme to reduce drying and storage loss could probably result in 10–20% increase in the food available in some of the developing countries, and the increased food supply could be used for the nourishment of hungry people in the developing countries.

Drying and storage are a part of food production system consisting of two subsystems – crop production and post-harvest operation. Efficiency of the system can only be increased by a coordinated effort of a multidisciplinary team consisting of agriculturists, agricultural engineers, economists and social scientists for increased crop production and reduction of post-harvest losses. The reduction in post-harvest losses depends on the proper threshing, cleaning, drying and storage of the crops. A reduction in crop loss at one stage may have a far-reaching effect on the overall reduction of the loss. For example, overdrying of paddy will increase the storage life but it will also increase the breakage percentage of the rice during milling. This suggests that a systems approach is essential for increasing the efficiency of food production system. Food security can be increased through increasing production and reducing post-harvest losses of the crops (Majumder *et al.*, 2016). This implies that considerable emphasis should be given not only on crop production but also on drying and storage process.

1.2 Losses of Crops

As mentioned earlier proper harvesting, drying and storage are essential to reduce losses of farm crops. Loss of harvested crops may be quantitative or qualitative and may occur separately or together. One of the basic problems in loss estimates is the definition of the term 'loss'. The following brief descriptions are intended to demonstrate the different types of loss.

Weight Loss: Weight or quantity loss is the loss of weight over a period under investigation. There are two types of weight loss – apparent weight loss and real weight loss. Apparent weight loss is the loss of weight during any post-harvest operation under study. This loss does not consider the effect of the moisture content or the contamination with insects, fungi and foreign materials. The real weight loss is the apparent weight loss with the correction for any change in moisture content, plus dust, frass, insects and so on.

Nutritional Loss: Any loss in weight of the edible matter involves a loss of nutrients. Thus, weight loss can be used to estimate nutritional loss.

Quality Loss: Damaged grains and contaminants, such as insect fragments, rodent hairs and pesticide residues, within the grain cause the loss of quality, resulting in monetary loss. Similarly, changes in the biochemical composition, such as increase in free fatty acid content, may also rank as losses in quality.

Loss of Viability: Loss in viability of seed is one of the losses easiest to estimate and is apparent through reduced germination, abnormal growth of rootlets and shoots and reduced vigour of the plant.

Indirect Loss: Indirect losses involve commercial relationship which may not be quantified easily. This includes goodwill loss and social loss.

The crop losses discussed in the preceding text are mainly quantitative and qualitative losses. The major factors in quality loss appear to be from insect damage, damage by fungi, broken grain, dust and other foreign materials.

1.3 Importance of Drying

Drying has the following important advantages:

- 1) Drying permits the long-time storage of grains without deterioration of quality.
- 2) Drying permits farmers to have better-quality product for their consumption and sale.
- 3) Drying permits the continuous supply of the product throughout the year and takes advantage of higher price after harvesting season.
- 4) Drying permits the maintenance of viability and enables the farmers to use and sell better-quality seeds.
- 5) Drying permits early harvest which reduces field damage and shatter loss.
- 6) Drying permits to make better use of land and labour by proper planning.

1.4 Principles of Drying

Drying is the removal of moisture to safe moisture content and dehydration refers to the removal of moisture until it is nearly bone dry. Generally, drying is defined as the removal of moisture by the application of heat, and it is practised to maintain the quality of grains

during storage to prevent the growth of bacteria and fungi and the development of insects and mites. The safe moisture content for cereal grain is usually 12–14% moisture on a wet basis.

Heat is normally supplied to the grains by heated air naturally or artificially, and the vapour pressure or concentration gradient thus created causes the movement of moisture from inside of the kernel to the surface. The moisture is evaporated and carried away by the air.

Drying capacity of the air depends on air temperature, moisture content of the grain, the relationship between the moisture content of the grain and the relative humidity of the drying air and grain type and maturity. The temperature of the drying air must be kept below some recommended values depending on the intended use of the grain. Safe maximum temperature of drying seed grains and paddy grains is 43°C, and for milling wheat the maximum recommended temperature is 60°C. Excessive high-temperature drying causes both physical and chemical changes and, especially in the case of rice, increases the percentage of breakage of whole rice and reduces the quantity and quality of rice. However, in cases of malt and tea, high-temperature drying is essential for desired physical and chemical changes for their ultimate use as drinks.

Reference

Majumder, S., Bala, B.K., Fatimah, M.A., Hauque, M.A. and Hossain, M.A. 2016. Food security through increasing technical efficiency and reducing post harvest losses of rice production systems in Bangladesh. *Food Security*, 8(2): 361–374.

Further Reading

Adams, J.M. 1977. A review of the literature concerning losses in stored cereals and pulses published since 1964. *Tropical Science*, 19(1): 1–28.

Bala, B.K. 1997. *Drying and storage of cereal grains*. Oxford & IBH Publishing Co, New Delhi.

Hall, C.W. 1980. *Drying and storage of agricultural crops*. AVI Publishing Company Inc, Westport, CT.

2

Moisture Contents and Equilibrium Moisture Content Models

2.1 Introduction

Moisture contained in a grain is an indicator of its quality and a key to safe storage and can be of two types: 'water of composition', called absorbed water, which is contained within the plant cells of which the grain kernel is composed of and adsorbed water which is present on the surface but not within the cells. The moisture content of the grains may be determined on farms, in stores and under laboratory conditions. These necessitate some standards for representation of moisture content and methods of its measurement.

2.2 Moisture Content Representation

Moisture content is usually expressed in per cent of moisture present in the grain, and there are two methods for expressing these percentages: (i) wet basis and (ii) dry basis.

Moisture content of a grain on a wet basis is expressed as the ratio of the weight of water present to the total weight of the grain. It is normally expressed in per cent. Moisture content on a wet basis is used for commercial designation and also universally by farmers, agriculturalists and merchants. This method of expression tends to give incorrect impression when applied to drying since both moisture content and the basis on which it is computed change as drying proceeds. For this reason moisture content on a dry basis is used in many engineering calculations and mainly used by researchers.

Moisture content on a wet basis is given by

$$M_w = \frac{W_w}{W_w + W_d} \quad (2.1)$$

Alternatively, moisture content on a dry basis compares the weight of the moisture present with the weight of dry matter in the grain. This can be expressed as

$$M_d = \frac{W_w}{W_d} \quad (2.2)$$

It may be necessary to convert moisture content from wet basis to dry basis, and vice versa. To convert moisture content from a wet basis to a dry basis, subtract each side of Equation 2.1 from 1.

$$1 - M_w = 1 - \frac{W_w}{W_w + W_d} \quad (2.3)$$

This equation on simplification gives

$$M_d = \frac{M_w}{1 - M_w} \quad (2.4)$$

To convert moisture content from a dry basis to a wet basis, Equation 2.2 may be rewritten as

$$1 + M_d = 1 + \frac{W_w}{W_d} \quad (2.5)$$

This equation on simplification yields

$$M_w = \frac{M_d}{1 + M_d} \quad (2.6)$$

Example 2.1

2000 kg of freshly harvested paddy with a moisture content of 25% (d.b.) is dried to a moisture content of 14% (d.b.). Determine the final weight of the grain after drying.

Solution

From Equation 2.5, we can write

$$\frac{W_w + W_d}{W_d} = 1 + M_d$$

Here $W_{25} + W_d = 2000$ kg and $M_d = 0.25$

$$\text{Hence } W_d = \frac{2000}{1 + 0.25} = 1600 \text{ kg}$$

Again for 12% m.c.,

$$W_d + W_{12} = 1600 \times (1 + 0.12) = 1792 \text{ kg}$$

Hence the final weight of the dried grain is 1792 kg.

Example 2.2

8000 kg of paddy with a moisture content of 0.12 (d.b.) is required for a research project on grain storage. It was decided that the available freshly harvested paddy with a moisture content of 0.20 (w.b.) should be procured, and then it will be dried to a moisture content of 12% on a dry basis. How many kilograms of freshly harvested paddy are to be procured?

Solution

From Equation 2.5, we can write

$$\frac{W_w + W_d}{W_d} = 1 + M_d$$

Here $W_d + W_{12} = 8000$ kg and $M_d = 0.12$

$$\text{Hence } W_d = \frac{8000}{1 + 0.12} = 7142.86 \text{ kg}$$

Again from Equation 2.4,

$$M_d = \frac{M_w}{1 - M_w}$$

For $M_w = 0.20$,

$$M_d = \frac{0.20}{1 - 0.20} = 0.25$$

Again for 25% m.c. (d.b.),

$$W_d + W_{25} = W_d \times (1 + M_{25}) = 7142.86 \times (1.25) = 8928.58 \text{ kg}$$

Hence 8928.58 kg of freshly harvested paddy is to be procured.

Example 2.3

Ten tonnes of rice is dried from an initial moisture content of 22.0 to 12% (w.b.) in a batch dryer using diesel fuel. Calculate (i) how much diesel is needed and (ii) cost of drying per kg. Use latent heat of vaporization of moisture = 10 MJ/kg, heating value of diesel = 42.7 MJ/l and price of diesel = Tk. 55.0/l.

Solution

The initial moisture content on a dry basis is

$$M_d = \frac{M_w}{1 - M_w} = \frac{0.22}{1 - 0.22} = 0.2821$$

and the final moisture content on a dry basis is

$$M_d = \frac{M_w}{1 - M_w} = \frac{0.12}{1 - 0.12} = 0.1364$$

Moisture in the grain is

$$\text{Moisture present} = 10,000 \times 0.22 = 2,200 \text{ kg}$$

and the dry matter is

$$W_d = 10,000 - 2,200 = 7,800 \text{ kg}$$

The moisture removal is given by

$$\text{Moisture removal} = \text{dry matter} \times (M_o - M_f) = 7800 \times (0.2821 - 0.1364) = 1136.46 \text{ kg}$$

Diesel needed is given by

$$\text{Diesel needed} = \frac{1136.46 \times 10}{42.7} = 266.151$$

Cost of drying per kg is given by

$$\text{Cost per kg} = \frac{266.15 \times 55}{10,000} = 1.46 \text{ Tk./kg}$$

2.3 Determination of Moisture Content

Determination of moisture content of a grain is essential to know its keeping quality. It is also important to know the moisture content during drying and storage. Price of grains depends on moisture content. Again, if the farmers sell overdried grains, they sell the dry

matter of grains for the price of water. For underdried grains the farmers are offered lower prices. Also the quality of the grains will deteriorate soon during storage. These also emphasize further the need to determine the moisture content of cereal grains.

The methods of determining moisture content can be classified as (i) direct method and (ii) indirect method. Direct method involves the actual removal of moisture and its measurement. The moisture contents are expressed either on a wet basis or on a dry basis. The following are the common methods for direct determination of moisture content:

- 1) Oven method
- 2) Infrared lamp method
- 3) Brown–Duvel method

Indirect method involves the measurement of some properties related to the moisture in grains. The moisture content is expressed on a wet basis. This method is much quicker but less accurate. The instrument has to be calibrated against a primary method. The following are the common methods for determining moisture content through the measurement of some parameters of moisture contained in the grains:

- 1) Resistance method
- 2) Capacitance method
- 3) Chemical method
- 4) Relative humidity method

2.3.1 Direct Methods

2.3.1.1 Oven Methods

Operating conditions and procedures are different for various materials. Air oven method or water oven method may be used for direct determination of moisture content, but the air oven method is commonly used for grains.

Air Oven Method, $130 \pm 1^\circ\text{C}$

- a) One-stage method (for grains under 13% moisture content)
 - a) Grind duplicate samples of 2–3 g each and weigh accurately.
 - b) Heat for 1 h at 130°C .
 - c) Remove from oven and place in a desiccator. Then reweigh. Samples should be within 0.1% moisture content of each other.

$$\text{Moisture content \% (w.b.)} = \frac{(\text{initial weight of sample} - \text{final weight of sample})}{\text{initial weight of sample}} \times 100$$

- b) Two-stage method (for grains over 13% moisture content)
 - a) Weigh accurately a 25–30 g sample of whole grain.
 - b) Place in the oven for 14–16 h.
 - c) Remove from the oven and place in a desiccator. Then reweigh.
 - d) Grind a sample of the partially dried grain and proceed for the one-stage method.

Water Oven or Air Oven method, 100°C

- a) Weigh two 25–30 g samples accurately and place them in the oven.
- b) Heat for 72–96 h at 90–100°C.
- c) Remove from the oven and place in the desiccator. Then reweigh. Sample should be within 0.1% moisture content of each other.

An alternative approach is to use a vacuum oven. Grain is ground and placed in the oven at 100°C and 25 mm pressure for approximately 5 h.

The grain sample should be in the oven until weight loss stops. It is practically impossible to remove all the moisture from grains without their deterioration. If the grain samples are kept too long in the oven, organic materials of the samples will be lost, and these will appear as moisture loss and give inaccurate value. So moisture content should be determined according to the standards set by the professional organization and/or government regulations.

2.3.1.2 Infrared Lamp Method

Moisture meter employing infrared lamp is available commercially. Moisture content is measured directly by the evaporation of water from the grain sample by heating with an infrared lamp. Milling of grain sample is not essential, but this will reduce the time required for the evaporation of water from the grain sample.

This meter consists of a balance and an infrared lamp. The pan of the balance is counterbalanced by a fixed and an adjustable weight along a lever. There is also a scale calibrated in moisture content. The infrared lamp is mounted on a swivelling arm above the pan.

The procedures for measuring moisture content are as follows:

- 1) Set the balance at a zero position by placing the moisture content indicator at zero position.
- 2) Weigh a fixed amount of the sample accurately.
- 3) Place the sample on the pan of the balance at zero position and place equal weight on the counterbalance such that the balance indicates zero position and the moisture content indicator is at 0% moisture level.
- 4) Heat the sample by infrared lamp until weight loss stops.
- 5) Set the balance again at the zero position by shifting the moisture content indicator.
- 6) Read the moisture content in per cent from the calibrated scale indicated by the pointer.

The range of moisture content that can be read is from 0 to 100%. If the sample to be tested is so wet that it cannot be milled, it should be pre-dried to reduce the time required for moisture content determination. It is interesting to note that this meter does enable the determination of high moisture contents.

2.3.1.3 Brown–Duvel Method

In this method a sample of grains is placed in an oil bath and heated to a temperature above that of boiling water but below the distillation temperature of the oil. The weight of water vapour driven off is determined by collecting the condensed vapour in a measuring cylinder or by measuring the weight of the sample. A grain sample of 100 g is heated in a flask containing 150 ml of oil for about 1 h.

In modified Brown–Duvel method the water driven off from the sample being tested by heating in vegetable oil is measured, and the moisture content is determined.

The apparatus required are:

- 1) A balance capable of weighing 1.5 kg accurately to at least 1 g
- 2) One 2 l saucepan
- 3) One thermometer graduated at 0–220°C in 1°C intervals
- 4) One stirring rod
- 5) Supply of vegetable oil such as domestic cooking oil
- 6) Source of heat such as electric hot plate or camping stove

The test procedures are as follows:

- 1) Place the saucepan containing the stirring rod on the balance and add oil until it is approximately half full. Additional quantity of oil should be added until the balance is 'tared'.
- 2) Add exactly 100 g of the grain sample in the oil, when the total weight of the saucepan, oil and sample is 900–1500 g.
- 3) Heat the saucepan and stir the sample regularly until the temperature reaches 190°C. This should take 10–15 min.
- 4) Reweigh the saucepan.

With 100 g sample the moisture content is equal to the loss in weight. When the sample is not exactly 100 g, the moisture content should be calculated. The principal advantage of this method is that the moisture contents beyond the range of indirect electric moisture meters can be measured.

2.3.2 Indirect Methods

2.3.2.1 Resistance Methods

The electrical resistance or conductivity of a material varies with its moisture content. The electrical resistance-type moisture meters measure the electrical resistance of grain as the criterion of grain moisture content, and these meters are calibrated against a standard method. For wheat it has been found that the logarithm of electrical resistance is linearly related to moisture content over the range 11–16%. The electrical resistance of grain varies with temperature, and the reading of the meter should be corrected for temperature when the temperature of the operating condition differs from the calibrated conditions. Most of the models of this type of meters incorporate a compression cell which may be an integral part of the meter or remote from it. The electrical resistance of grains decreases when pressure is increased. The cell contains two electrodes between which the electrical resistance of the sample is measured. Such cells incorporate a device which ensures that the sample is consistently compressed to a predetermined extent.

Above 17% of moisture content, the relationship between the moisture content and the logarithm of electrical resistance is parabolic. Most meters do not give reading below 7% because there is little change in electrical resistance with moisture content.

The accuracy of the resistance-type meters is dependent on the uniform distribution of the moisture throughout the grain. Recently dried grains tend to give low readings if the surface of the grain is disproportionately dry. Conversely, freshly wet grains may give high readings. Some models of this type of meter can be used with either milled or

unmilled grain, the former being more recommended for greater accuracy. This type of meter is most accurate at the moisture content which is required for prolonged storage of grains in bulk.

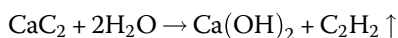
2.3.2.2 Capacitance Methods

The dielectric properties of products depend on the moisture content. Hence, the capacitance of an electrical condenser varies with the moisture content, with the product placed between its plates. Wet materials have a high dielectric constant, whereas dry materials have a low dielectric constant. Water has a dielectric constant of 80 at 20°C, and most grains have a value less than 5. The measurement of capacitance is an indirect measurement of the moisture content.

This type of meters often incorporates a chamber wherein the materials to be tested are placed. Two sides of the chamber form the plates of a condenser between which a high-frequency current is passed to measure the capacitance of the sample. Capacitance meters are generally capable of determining a wider range of moisture content than a resistance type, that is, for wheat 8–40%. These meters are also less susceptible than resistance meters to errors arising from uneven moisture distribution within the sample but tend to be more difficult to keep in adjustment.

2.3.2.3 Chemical Methods

Water from a grain sample can be removed by adding a chemical which decomposes and combines with water. When calcium carbide is mixed with the grain sample, the moisture in the grain reacts with the chemical, resulting in the production of acetylene gas.



The volume of gas produced is proportional to the moisture in the grain. Moisture meters are available which operate on this principle.

Approximately 30 g of the grain sample is mixed in a sealed vessel with an excess quantity of calcium carbide. After 15–20 min the calcium carbide reacts with the moisture present to liberate acetylene. The pressure generated by the gas enables a direct reading of moisture content on the pressure gauge mounted on the base of the meter.

2.3.2.4 Relative Humidity Methods

The air in the inter-granular space in a grain mass reaches a state of equilibrium with the moisture content of the grain. Hence, when stable conditions are established, it is feasible to measure the relative humidity and express the result as a moisture content.

A simple device of this type consists of a probe which encapsulates sensitive hair elements. Ventilation is provided through the holes of the probe, which aids the circulation of air around the sensing elements. The sensing elements expand and contract in response to the changes in the relative humidity in the air. The elements are connected to a needle on a scale and calibrated in both relative humidity and moisture content.

This type of meter takes up to 30 min to respond to the relative humidity of the air in a grain mass, and the readings should not be taken until the pointer is stable. Exact accuracy cannot be anticipated in this type of meter. When moisture content exceeds 22%, inaccuracy can be anticipated, because the relative humidity becomes almost 100%

regardless of grain moisture content. If an inexpensive direct reading instrument is required, this type should be considered.

2.4 Grain Sampling

The accuracy of determination of grain moisture content depends not only on the accuracy of the moisture meters but also on the method of sampling, size and number of samples. It is important that the sample be a representative of the product.

When the moisture content of a batch of grains is assessed, representative samples of that batch should be ensured. The extent to which the samples are representative of the whole batch depends on the variability of that batch and the thoroughness of sampling. Various organizations recommend precise methods of sampling, such as British Standards Institute.

A primary sample is defined as a small quantity of grain taken from a single position in the lot, and all primary samples should be of similar size and weight. Sampling spears are available and standard samplers will normally penetrate a depth of approximately 3 m. The selection of correct locations is also of significance. The sampling position should be selected impartially so that the top, bottom and sides of the grain mass are equally represented. Special care should be taken to ensure that a disproportionate quantity of grain from its exposed surfaces is not included in the samples. It is also important that moisture content of the grains be maintained from the time of sampling until its determination. Standard metal containers and film bags prescribed by the government or professional organizations should be used for holding the samples.

2.5 Equilibrium Moisture Content

The equilibrium moisture content (EMC) of a cereal grain is defined as the moisture content of the material after it has been exposed to a particular environment for an infinitely long period of time. EMC is dependent upon the relative humidity and temperature conditions of the environment and upon the species, variety and maturity of the grain. EMC may be classified as (i) static EMC and (ii) dynamic EMC. The concept of dynamic EMC was introduced by McEwen *et al.* (1954). The dynamic EMC is obtained best by fitting the thin layer drying equation to experimental data, whereas the static EMC is obtained after a prolonged exposure of the product to a constant atmosphere. McEwen, Simmonds and Ward further suggested that dynamic and static EMCs should be used for drying and storage design, respectively.

The relationship between the moisture content of any material and its equilibrium relative humidity at a constant temperature can be represented by a curve (Figure 2.1) called an isotherm. At normal atmospheric pressure, the values of moisture content which are reached are mainly dependent on relative humidity and to a much lesser extent on temperature. Often it is seen in practice that temperature is the more important factor. This is because of the relative humidity of the moist air which is temperature dependent. However, there is generally a reduction in moisture content for a fixed relative humidity as the temperature is increased. Figure 2.2 shows EMC changes with relative humidity of

Figure 2.1 Sorption isotherm, desorption isotherm and hysteresis of moisture sorption of wheat at 35°C.

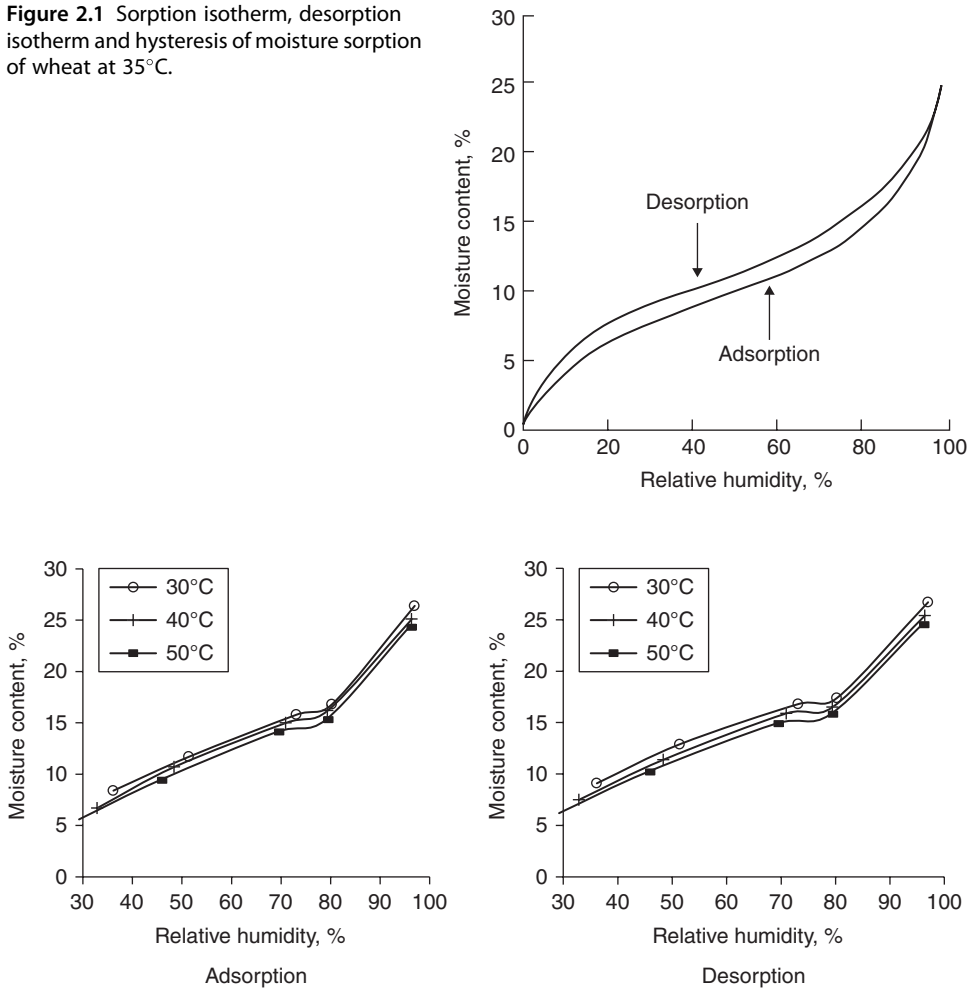


Figure 2.2 Adsorption and desorption isotherms of hybrid rice at 30°C, 40°C and 50°C.

hybrid rice at 30, 40 and 50°C and shows that EMC decreases with the increase in temperature. EMC of major cereal grains is shown in Table 2.1.

A sorption isotherm is a plot of EMC versus relative humidity at a given temperature for a material which has been subjected to a wetting environment. A desorption isotherm is a similar plot for a material which has been subjected to a drying environment. The difference between the desorption and adsorption isotherms at a given temperature for a material is termed as the hysteresis effect (Figure 2.1), and this suggests that the EMC of a given material is not only a function of its immediate environment but also affected by the previous moisture condition. Several theories and hypotheses have been advanced to explain the hysteresis and subsequent disappearance of hysteresis loop initially exhibited in successive adsorption and desorption cycles. Chung and Pfof (1967c) explained these phenomena of hysteresis effect and disappearance of hysteresis loop by the concepts of molecular shrinkage in adsorption caused by activation and crack

Table 2.1 Grain equilibrium moisture content, % (wb).

Material	Temperature, °C	Relative humidity, %									
		10	20	30	40	50	60	70	80	90	100
Barley	25	4.4	7.0	8.5	9.7	10.8	12.1	13.5	15.8	19.5	26.8
Buckwheat	25	5.0	7.6	9.1	10.2	11.4	12.7	14.2	16.1	19.1	24.5
Cottonseed	25				6.9	7.8	9.1	10.1	12.9	19.6	
Dry beans	4						12.8	14.4	17.0		
Michelite	10						13.8	15.3	18.0		
	25	5.6	7.4	8.6	9.8	11.2	12.9	14.9	17.5		
	38						12.0	14.2	17.1		
	54						12.4	14.3	18.5		
Dry beans											
Red Mexican	25	6.0	7.5	8.6	9.8	11.0	12.8	15.2	18.6		
Great Northern	25	5.9	7.4	8.5	9.6	10.9	12.6	15.0	18.0		
Light-red kidney	25	6.1	7.5	8.7	9.9	11.1	12.9	15.1	18.5		
Dark-red kidney	25	5.4	7.2	8.4	9.6	10.7	12.5	15.0	18.6		
Flat small white	25	6.0	7.1	8.3	9.6	11.0	12.6	15.0	18.1		
Pinto	25	6.1	7.4	8.5	9.8	11.0	12.6	15.2	18.2		
Flaxseed	25	3.3	4.9	5.6	6.1	6.8	7.9	9.3	11.4	15.2	21.4
Oats	25	4.1	6.6	8.1	9.1	10.3	11.8	13.0	14.9	18.5	24.1
Rice, whole grain	25	5.9	8.0	9.5	10.9	12.2	13.3	14.1	15.2	19.1	
Whole grain	38	4.9	7.0	8.4	9.8	11.1	12.3	13.3	14.8	19.1	
Milled	25	5.1	7.6	9.0	10.3	11.5	12.6	13.8	15.4	18.1	23.6
Rice	27				9.2	10.4	11.7	13.2	15.0	17.1	

Table 2.1 (continued)

Material	Temperature, °C	Relative humidity, %									
		10	20	30	40	50	60	70	80	90	100
Wheat											
Soft-red winter	-7				11.3	12.8	14.1	15.6	17.0		
	0				11.0	12.2	13.5	14.7	16.2		
	10				10.2	11.7	13.1	14.4	16.0		
	21				9.7	11.0	12.4	14.0			
	25	4.3	7.2	8.8	9.7	10.9	11.9	13.6	15.7	19.7	25.6
Hard-red winter	25	4.4	7.2	8.5	9.7	10.9	12.5	13.9	15.8	19.7	25.0
Hard-red spring	25	4.4	7.2	8.5	9.8	11.1	12.5	13.9	15.9	19.7	25.0
White	25	5.2	7.5	8.6	9.4	10.5	11.8	13.7	16.0	19.7	26.3
Durum	25	5.1	7.4	8.5	9.4	10.5	11.5	13.1	15.4	19.3	26.7
Wheat	25	5.8	7.6	9.1	10.7	11.6	13.0	14.5	16.8	20.6	
Wheat	50	4.0	5.8	6.7	8.1	10.0	10.8	12.6	15.1	19.4	

Source: Bala (1997).

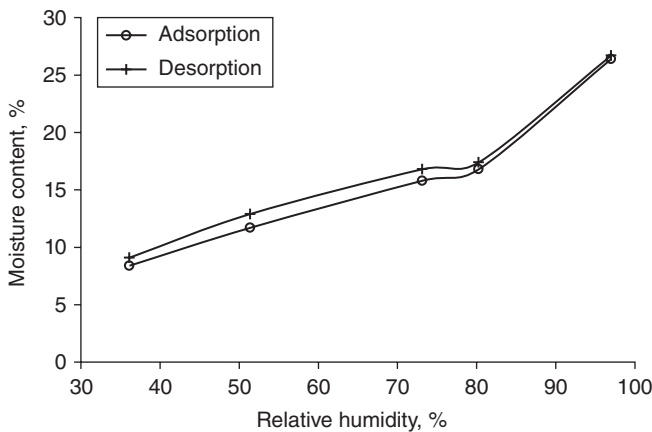


Figure 2.3 Desorption and adsorption isotherms of rough rice at 30°C.

formation caused by wetting during the successive cycles of the sorption process, respectively. Figure 2.3 shows desorption and adsorption isotherms of hybrid rough rice at 30°C, and desorption isotherm is at higher moisture content than adsorption isotherm.

2.6 Determination of Static Equilibrium Moisture Content

There are two general methods for determining the static EMC: (i) static method and (ii) dynamic method. In the static method the grain is allowed to come to equilibrium in still and moist air. Saturated salt or acid solution is normally used to maintain the relative humidity in this method. The dynamic method is quicker but complicated in design and instrumentation. In dynamic method the air is mechanically moved around the sample in a closed chamber containing a dew point apparatus or an either salt or acid solution. It is also important to measure moisture content as accurately as determining and maintaining relative humidity in the closed chamber. The dew point method is extensively used in the United Kingdom, whereas the chemical method of known relative humidity maintained by a saturated salt or acid solution is extensively used in the United States (static method).

The dynamic method requires a couple of days or less, but the static method may take several weeks. At high relative humidities mold may grow in the grains and give apparently a high moisture content. The moisture content obtained above 80% relative humidity is not a true moisture content. The dynamic method is faster and is extensively used.

A saturated salt or acid solution may be used to maintain the relative humidity in the closed chamber. A salt solution is more stable, less corrosive and often less expensive. A saturated salt solution can be maintained easily and remains saturated even after the evaporation of water but precipitates some of the salt. To maintain relative humidity between 0 and 100%, a large number of salts are required, but a saturated salt solution can easily be prepared by dissolving all the salts at a temperature above the desired temperature. Table 2.2 lists the relative humidity values at different temperatures for a large number of salts (Hall, 1980).