FOOD DRYING

Proceedings of a Workshop
Held at Edmonton, Alberta, 6-9 July 1981
The International Development Research Centre is a public corporation created by the Parliament of Canada in 1970 to support research designed to adapt science and technology to the needs of developing countries. The Centre's activity is concentrated in five sectors: agriculture, food and nutrition sciences; health sciences; information sciences; social sciences, and communications. IDRC is financed solely by the Parliament of Canada; its policies, however, are set by an international Board of Governors. The Centre's headquarters are in Ottawa, Canada. Regional offices are located in Africa, Asia, Latin America, and the Middle East.

©1982 International Development Research Centre
Postal Address: Box 8500, Ottawa, Canada K1G 3H9
Head Office: 60 Queen Street, Ottawa

Yaciuk, G.  
IDRC-195e


UDC: 664.8.047  
ISBN: 0-88936-333-1

Microfiche edition available
Food Drying

Proceedings of a workshop held at Edmonton
Alberta, 6–9 July 1981

Editor: Gordon Yaciuk

Sponsored by
International Development Research Centre,
Ottawa, Canada

in collaboration with
Alberta Department of Agriculture,
Edmonton, Canada
Abstract/Résumé/Resumen

The authors of this volume include researchers and scientists from many countries that encompass diverse climatic, geographic, and socioeconomic conditions. Their disciplines were also numerous: home economics, food science, nutrition, physics, and engineering.

The workshop covered the most important areas in the design and operation of a drying system. These are: drying requirements, consumer acceptance, heat and mass transfer, and heat sources. Within drying requirements, the need for drying the product is discussed as well as drying times and rates, sample preparation, quality changes during drying, rehydration problems, and problems with storage of the dried product. The section on consumer acceptance includes the effects of drying on the nutritive value of food, the introduction of a dried food to the consumer market, and how consumers provide valuable information to scientists to help in improving a process or product. The theory and design of a drying chamber and process control are explained under heat and mass transfer and an operational, full-scale drying system is examined. Finally, under heat sources, a number of examples are given in the use of the sun, petroleum products, agriculture wastes, and wood as heat sources for a drying process. A final concluding commentary is made on the overall recommendations derived from the workshop and proposals for future work are given.

Les auteurs de ce volume sont des chercheurs et des techniciens venus de pays très différents les uns des autres du point de vue climat, géographie et conditions socio-économiques. Les disciplines représentées étaient aussi très diverses: économie domestique, alimentation, nutrition, physique, génie mécanique.

Le colloque a examiné les questions les plus importantes en ce qui concerne la conception et l'utilisation d'une installation de séchage: besoins en matière de séchage, l'accueil du consommateur, transmission de la chaleur et évacuation de l'humidité, sources de chaleur. Le chapitre sur les besoins en matière de séchage traite de la nécessité et de la durée de cette opération, de la préparation des échantillons, de l'action du séchage sur la qualité du produit, des problèmes de réhydratation et des problèmes de stockage du produit sec. Le chapitre sur l'accueil du consommateur traite des effets du séchage sur la valeur nutritive du produit, de la commercialisation d'un produit sec et de l'aide que peuvent apporter les consommateurs à l'amélioration d'un procédé ou d'un produit. Le chapitre sur la transmission de la chaleur et l'évacuation de l'humidité traite de la théorie et de la conception d'un séchoir, des modes de réglage et décrit une installation en service. Enfin, le chapitre sur les sources de chaleur donne des exemples de l'utilisation du soleil, des produits pétroliers, des déchets agricoles et du bois. Un exposé des conclusions dégagées par le colloque et de ses recommandations est présenté à la fin de l'ouvrage.

Los autores de este volumen comprenden investigadores y científicos de varios países que, en conjunto, abarcan diversas condiciones climáticas, geográficas y socio-económicas. Sus disciplinas respectivas también son numerosas: economía del hogar, ciencias de alimentación, nutrición, física e ingeniería.

El cursillo abarcó los aspectos más importantes en el diseño y operación de un sistema de deshidratación. Estos son: requisitos de la deshidratación, aceptación por el consumidor, trasferencia de calor y masa y fuentes de calor. Entre los requisitos se examina la necesidad de deshidratar el producto así como los tiempos e índices del proceso, preparación de muestras, cambios en calidad durante la deshidratación, problemas que presenta la rehidratación y problemas resultantes del almacenamiento del producto deshidratado. La sección de aceptación por el consumidor comprende los efectos de la deshidratación sobre el valor nutritivo del alimento, la introducción de un alimento deshidratado en el mercado del consumidor, y cómo éstos a su vez proveen información valiosa a los científicos ayudándoles a mejorar un proceso o producto. Se explican la teoría y diseño de la cámara de deshidratación y el proceso de control bajo trasferencia de calor y masa, examinándose un sistema operativo de deshidratación a escala comercial. Finalmente, bajo el concepto de fuentes de calor, se citan varios ejemplos relacionados con el uso del sol, de productos petrolíferos, y desechos agrícolas, así como el de la madera como fuentes de calor para procesos de deshidratación. Se efectúa un comentario final sobre recomendaciones generales derivadas del cursillo al tiempo que se efectúan propuestas para el trabajo futuro.
## Contents

**Foreword** .................................................. 5

**Participants** ............................................... 6

**Introduction**
Theme and objectives of the workshop G. Yaciuk .................. 9

**Drying Requirements**
- Drying of fish in India P.V. Prabhu and K.K. Balachandran ...... 11
- Drying of vegetables in Egypt H.M. Ali and I.A. Sakr ............ 15
- Drying of potatoes (papa seca) in Peru C. Lescano .............. 20
- Drying of paddy in Indonesia Suahyadi ........................ 27

**Consumer Acceptance**
- Effect of drying on the nutritive value of foods in Kenya M.I. Gomez ........................................... 31
- Designing cowpea products for Northeastern Thailand T. Ngarmsak, M.D. Earle, and A.M. Anderson ................. 36
- Consumer acceptance of dehydrated banana weaning food in Costa Rica Celsa Lastreto G., Rodney Cooke, and Armando Campos S. ......................................................... 40

**Heat and Mass Transfer**
- Drying of cereal grains in the Philippines S.C. Andales ........ 51
- Drying onions in Niger A. Ba, Ch. Banzet, and J.M. Degbe ....... 61
- Drying fish in the Philippines Ernesto V. Carpio ................ 63
- Drying grapes in northern Chile J.M. Olhagaray ................. 71

**Heat Sources**
- Solar energy as a heat source in crop drying in Sierra Leone Michael W. Bassey ........................................... 73
- Solar and natural air drying of rough rice in Korea Hak Kyun Koh and Chang Joo Chung .............................. 81
- Farm grain dryer — Thailand Sriwai Singhagajen ................. 89
- Dryers for cooperatives for food production in Indonesia Sjachputra .................................................. 99

**Conclusions**
Commentary G. Yaciuk ........................................ 103
Foreword

For as long as we have historical record, the heat of the sun has been used
to dry cereal grains, vegetables, fruit, fish, and meat. Solar radiation is widely
used as a direct source of energy by which to dry and dehydrate foods of many
kinds in many countries. As fossil fuel costs continue to rise, direct and indirect
solar drying will gain increasing importance as a method of food preservation
throughout the world.

The International Development Research Centre (IDRC) is supporting
several research projects in which solar radiation alone or together with
combusted agricultural wastes is used to dry crops and other food materials, in
several of which the influence of variable drying conditions upon nutrient
retention is being studied.

Because the food dehydration and crop drying projects financed by IDRC
are located in countries with widely different environmental conditions and the
spectrum of research activities calls for a variety of scientific disciplines, it
appeared desirable to bring together research workers representative of the
geographic and scientific diversity involved.

A workshop was, therefore, organized from 6 to 9 July 1981, at the
University of Alberta and in collaboration with the Alberta Department of
Agriculture (ADA), which included 2 days of formal sessions; a 1-day tour
organized by the ADA of a grain dryer manufacturing plant, a local farm, and a
primary elevator; and 1 day of informal visits to various university departments
and commercial organizations by individual participants. Those attending the
workshop came from Bangladesh, Chile, Egypt, Guatemala, India, Indonesia,
Kenya, Korea, Malaysia, Mali, Niger, Costa Rica, Peru, the Philippines, Sierra
Leone, Singapore, Thailand, and Zambia, encompassing immensely diverse
climatic, geographic, and socioeconomic conditions and with experience that
embraced home economics, food science, nutrition, physics, and engineering.
The main topics covered included drying requirements, consumer acceptance,
heat and mass transfer, and heat sources. This publication comprises the papers
presented and discussed, together with a commentary by the technical
coordinator of the meeting.

It is the belief of my colleagues in the Agriculture, Food and Nutrition
Sciences (AFNS) Division that, thanks to the contributions by those who took
part, this publication may prove of lasting value to others in developing
countries who share similar interests and concerns.

J.H. Hulse
Director
Agriculture, Food and Nutrition Sciences Division
Participants

A. Alam, Post-Harvest Technical Scheme Project Co-ordinator, Central Institute of Agricultural Engineering, Shri Guru Tegh Bahadur Complex, T.T. Nagar, Bhopal 462 003, India.

Hatem Mohamed Ali, Head, Laboratory on Animal and Poultry Nutrition, National Research Centre, Dokki, Cairo, Egypt.

Silvestre C. Andales, Assistant Professor and Project Leader, UPLB/IDRC Postharvest Project, Department of Agricultural Process Engineering, University of the Philippines at Los Baños, College, Laguna 3720, Philippines.

M. Zohadie Bardaie, Department of Agricultural Engineering, Universiti Pertanian Malaysia, Serdang, Selangor, Malaysia.

Michael W. Bassey, Department of Mechanical Engineering, Fourah Bay College, University of Sierra Leone, Freetown, Sierra Leone.

Ernesto V. Carpio, Project Engineer, Department of Food Science and Technology, University of the Philippines at Los Baños, College, Laguna 3720, Philippines.


Chong Thean Chhong, Chemical and Food Process Section, Singapore Institute of Standards and Industrial Research, Maxwell P.O. Box 2611, Singapore 9046, Republic of Singapore.

J.M. Degbe, Office national de l'énergie solaire, B.P. 621, Niamey, Niger.

Dante B. de Padua, Technical Team Leader. Southeast Asia Cooperative Post-Harvest Research and Development Programme, c/o SEARCA, College, Laguna 3720, Philippines.

W. Edwardson, Senior Program Officer, Agriculture, Food and Nutrition Sciences Division, International Development Research Centre, 10454 Whyte Avenue, Suite 304, Edmonton, Alberta, Canada.

R.S. Forrest, Associate Director, Engineering and Home Design Sector, Alberta Department of Agriculture, Agriculture Building, 9718 107 Street, Edmonton, Alberta, Canada.

Ricardo García, Engineer, Applied Research Division, Instituto Centro-americano de Investigación y Tecnología Industrial, Avenida La Reforma 4-47 Zone 10, Apartado Postal 1552, Guatemala, C.A.

Celsa Lastreto Gomez, Centro de investigaciones en Tecnología de Alimentos, Universidad de Costa Rica, San Jose, Costa Rica.

M.I. Gomez, Lecturer, Department of Food Science and Technology, Faculty of Agriculture. University of Nairobi, P.O. Box 29053, Kabete, Nairobi, Kenya.

H.K. Koh, Associate Professor, Division of Agricultural Machinery and Process Engineering, Department of Agricultural Engineering, College of Agriculture, Seoul National University, Suweon, Korea 170.
Carlos Lescano, Jefe, Departamento de Tecnología de Alimentos y Productos Agropecuarios, Universidad Nacional Agraria La Molina, Apartado 456, Lima, Peru.

J. Lorenzana, Agricultural Engineering Department, Isabela State University, Echaque, Isabela, Philippines.

Joseph M. Mwale, Senior Scientific Officer, Food Technology Research Unit, National Council for Scientific Research, P.O. Box CH-158, Chelston, Lusaka, Zambia.

Candido Joven Miguel, Pasig Distributors Corporation, 114 Plaza Rizal, Pasig, Metro Manila, Philippines.

Tipvama Ngarmsak, Department of Agricultural Products, Faculty of Agriculture, Khon Kaen University, Khon Kaen, Thailand.

J.M. Olhagaray, Institute of Technological Research (INTEC/CHILE), Casilla 667, Santiago de Chile, Chile.

P.V. Prabhu, Scientist, Central Institute of Fisheries Technology, CIFT/IDRC Fish Processing Project, Willingdon Island, Matsuropuri P.O., Cochin 682 029, India.

Abdus Satter, Senior Scientific Officer, Agricultural Engineering, Bangladesh Agricultural Research Institute, Joydebpur, Dacca, Bangladesh.

O.G.A. Schmidt, Program Officer, Agriculture, Food and Nutrition Sciences Division, International Development Research Centre, 10454 Whyte Avenue, Suite 304, Edmonton, Alberta, Canada.

Sriwai Singhagajen, Chief, Storage and Processing Section, Agricultural Engineering Division, Department of Agriculture, Ministry of Agriculture and Cooperatives, Bangkhen, Bangkok 9, Thailand.

Wenceslao M. Sison, Agricultural Plans and Programs Supervisor/Project Leader, Technical Research and Services Directorate, National Food Authority, 101 E. Rodriguez Sr. Avenue, Matimyas Building, Quezon City, Philippines.

Sjachputra, c/o Haji Muslimin Nasution, Ministry of Co-operatives, Departemen Perdagangan Dan Koperasi, Sekretariat Menteri Muda Urusan Koperasi, P.O. Box 384, Jakarta, Indonesia.

Suahyadi, Project Leader, National Logistics Agency (BULOG), BULOG/IDRC Postharvest Rice Technology Project, P.O. Box 2345, Jakarta, Indonesia.


Salomon Chavez Tapia, Departamento de Tecnologia Pesquera, Universidad Nacional Agraria La Molina, Apartado 456, Lima, Peru.

Cheick Oumar Traoré, Laboratoire de l'énergie solaire, B.P. 134, Bamako, Mali.

S. Vogel, Program Officer, Agriculture, Food and Nutrition Sciences Division, International Development Research Centre, 10454 Whyte Avenue, Suite 304, Edmonton, Alberta, Canada.

G. Yaciuk, Program Officer, Agriculture, Food and Nutrition Sciences Division, International Development Research Centre, 10454 Whyte Avenue, Suite 304, Edmonton, Alberta, Canada.
IDRC Staff

M.C. Beaussart, Administrative Assistant, Agriculture, Food and Nutrition Sciences Division, IDRC, 10454 Whyte Avenue, Suite 304, Edmonton, Alberta, Canada.

A. Chouinard, Technical Editor, Communications Division, IDRC, Box 8500, Ottawa, Ontario, Canada K1G 3H9.

K. Kealey-Vallière, Assistant Technical Editor, Communications Division, IDRC, Box 8500, Ottawa, Ontario, Canada K1G 3H9.
Solar and Natural Air Drying of Rough Rice in Korea

Hak Kyun Koh and Chang Joo Chung

Abstract. An evaluation was made of the feasibility of the solar and natural air in-bin drying and storage system, and the weather conditions and some experimental results conducted in Korea from 1973 to 1980 were analyzed. The experimental results of solar natural air drying were discussed in terms of drying rate, moisture variation in the grain mass, and energy requirements per kg of water removed.

Solar collectors with and without heat storage units were used for drying of rough rice. Economic profitability for the system developed is also analyzed in this paper.

The traditional method of rough-rice drying in Korea consists of sun drying in the field before threshing and sun drying on mats after threshing, which is laborious and highly weather dependent. With this method, a considerable loss both in quality and quantity of rough rice is unavoidable. Early cutting and threshing in the field have been recommended to prevent field losses. Because a new high-yielding variety was introduced in Korea in 1969, an improved drying operation has been urgently required to reduce the shattering loss in the field. In accordance with the new harvesting system using a combine or binder harvester, a mass drying of high-moisture grain has been required. However, Korean farmers are facing difficulties in the drying of high-moisture grain with the traditional sun-drying method.

The concept of natural-air drying and the application of solar energy to grain has received considerable attention in the past few years mainly because of the favourable weather conditions during the harvesting season in Korea. Furthermore, the application of solar energy to grain drying seems best suited to low-temperature systems. In addition, an in-bin drying system developed in this study would have an additional advantage because of its extended use as an improved storage system.

It was intended to evaluate the feasibility of the solar and natural air in-bin drying and storage system that is to be used at the farm level. For this purpose, the weather conditions, the average temperature and relative humidity, and some experimental results on solar and natural air drying conducted in Korea from 1973 to 1980 were summarized and reviewed.

Analysis of Weather Conditions for Natural Air Drying

In natural air-drying systems, the aeration method and the minimum amount of air flow are determined from the weather conditions and initial moisture content (MC) of grains, therefore, the feasibility of drying and storage using natural air must be studied on the basis of weather conditions over long periods. If weather conditions during the harvesting season have good drying potential, natural air drying is favourable, otherwise, heated air drying must be used. Drying potential of natural air can be measured by the dry-bulb temperature and relative humidity (RH) of natural air. To calculate a reasonable drying potential, weather data over a long period must be analyzed.

The investigators who conducted the natural air-drying experiments during 1973-80 also analyzed the weather data accumulated over 10 years to obtain the average temperature and relative humidity that determined the drying potential of natural air. Their analyses showed that the average temperature in October was in the range of 13.0-16.8°C and the relative humidity from 64 to 76%. Average temperature and relative humidity in October over 14 locations were 14.9°C and 69.4%, respectively.

From these analyses, the temperature and relative humidity in October provided high
drying potential because the equilibrium moisture content (MC) of grains was about 15% in this season. However, it must be noted that ideal weather conditions with high drying potential did not always occur during consecutive days. Sometimes, drying would be interrupted because of unsatisfactory weather conditions.

In the analysis of weather data, relative humidity was considered to be the most important weather factor for natural air drying. Kim (1974) assumed that the critical relative humidity (RHc) for natural air drying was 75%. Based on this assumption, Kim analyzed the weather data and reported that an optimum daily drying time in Suweon area was 9 hours. During 9 hours, the average temperature was in the range of 13–17.4°C and the relative humidity was 66%. These weather conditions were reported to have such high drying potential that the moisture content of grains was reduced as much as 14.2% wet basis (wb). By assuming that any day that had a relative humidity of more than 75% continuously for 3 hours or more was a nondrying day, Kim also reported that the Suweon area had 4 nondrying days in October. In the analysis of Kim et al. (1980), the Taegu area was also found to have 4 days of nondrying in October. Consequently, the weather conditions during the harvesting season in Korea could be considered as having high drying potential for natural air drying.

**Analysis of Natural Air-Drying Experiments**

To determine whether or not a natural air in-bin drying and storage system is feasible in a particular farm area, continuous experimental studies on natural air drying must be made over many years, because the efficiency of natural air drying using a grain bin varies depending upon the annual weather conditions in that area. The technical evaluation of the natural air in-bin drying and storage system must also be made on the basis of these experimental results. Table 1 summarizes the results of the natural air-drying experiments analyzed in this study. As shown in Table 1, six natural air-drying experiments employed similar experimental methods and showed similar results. All the experiments were conducted in October, and the drying period was about 10–15 days.

In experiments B, D, E, and F, the moisture content of grains was reduced to 15%, which was within the moisture content required for safe storage. However, in experiments A and C, moisture content could not reach 15% during the same drying period, because the amount of airflow in experiments A and C was less than those of the other experiments.

Average drying rate during the drying period was 0.03–0.11% per fan operation hour. This drying rate differed with fan operation methods such as continuous and intermittent operations. There were also significant differences in the drying rate between the beginning and final stages of drying.

Similar variations were observed in average moisture content during the drying period, although some differed depending on the area and time. The difference in the final moisture content (MCf) between the upper and bottom layers of grain was only within 1.0%, and a uniform drying progressed from the bottom to upper layers. No moisture gradient was observed in the radial direction within the grain bin. Consequently, natural air drying using a grain bin could be a very efficient drying method, although it does require a long drying period.

**Storage Experiment**

As previously mentioned, the grain bin performs the functions of both the grain dryer and storage unit. A rough-rice storage experiment using a grain bin was conducted at three locations. In the three experiments, analyses were made on the variations of the grain temperature and moisture content, which were considered to be important factors that affect the safe storage of rough rice.

From March to July of 1979, the average temperature of rough rice during storage gradually increased from 3 to 30°C and was generally higher than the ambient temperature as shown in Fig. 1. This higher temperature was attributable to the respiration heat of rough rice and convective heat transfer from outside the grain bin. During this period, average moisture content gradually increased from 13.5 to 15.3%. In general, during winter, little variation was observed in the grain temperature and moisture content inside the grain bin, but a large variation was observed during summer. Kim (1974) pointed out the storage problem resulting from the increase in grain temperature in summer. However, Chung and Koh (1980) showed in their experiment that safe storage in summer was possible even without aeration.

The milling test was conducted after the storage experiments were completed. The results of the milling test showed that brown rice recovery, milled rice recovery, and head rice
Table 1. Summary of drying experiments using natural air.

<table>
<thead>
<tr>
<th>Experiment no.</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section</td>
<td>3.8</td>
<td>3.14</td>
<td>2.25</td>
<td>2.01</td>
<td>4.33</td>
<td>7.1</td>
</tr>
<tr>
<td>area of bin (m²)</td>
<td>(ø2.2 m)</td>
<td>(ø2.0 m)</td>
<td>(1.5 x 1.5 m)</td>
<td>(ø1.6 m)</td>
<td>(ø2.35 m)</td>
<td>(ø8.0 m)</td>
</tr>
<tr>
<td>Height of bin (m)</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>1.2</td>
<td>1.2</td>
<td>2.5</td>
</tr>
<tr>
<td>Bin material</td>
<td>steel</td>
<td>steel</td>
<td>plywood</td>
<td>steel</td>
<td>steel</td>
<td>steel</td>
</tr>
<tr>
<td>Rough rice quantity (t)</td>
<td>3.6</td>
<td>2.0</td>
<td>1.7</td>
<td>1.0</td>
<td>2.3</td>
<td>4.2</td>
</tr>
<tr>
<td>Rice variety</td>
<td>Tong-il Milyang 23</td>
<td>Jinhung Milyang 23</td>
<td>Suweon 264</td>
<td>Milyang 30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rough rice depth</td>
<td>1.6</td>
<td>1.1</td>
<td>1.35</td>
<td>1.1</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Amount of air-flow (cm/m³)</td>
<td>2.8</td>
<td>4.0</td>
<td>1.64</td>
<td>3.60</td>
<td>3.60</td>
<td>4.81</td>
</tr>
<tr>
<td>Drying period</td>
<td>13/10/73-02/11/73</td>
<td>30/09/78-12/10/78</td>
<td>14/10/78-03/11/78</td>
<td>01/10/79-12/10/79</td>
<td>15/10/79-24/10/79</td>
<td>15/10/80-28/10/80</td>
</tr>
<tr>
<td>Initial moisture content (% wb)</td>
<td>22.2</td>
<td>20.0</td>
<td>24.8</td>
<td>19.8</td>
<td>20.0</td>
<td>24.4</td>
</tr>
<tr>
<td>Final moisture content (% wb)</td>
<td>16.7</td>
<td>14.0</td>
<td>15.1</td>
<td>13.7</td>
<td>13.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Fan operation time (hours)</td>
<td>107</td>
<td>210</td>
<td>325</td>
<td>207</td>
<td>66</td>
<td>288</td>
</tr>
<tr>
<td>Average drying rate (%/hour)</td>
<td>0.05</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.11</td>
<td>0.03</td>
</tr>
</tbody>
</table>

*Round steel bins were used for all the experiments except in experiment C where a rectangular plywood bin was installed.*

---

**Fig. 1.** Variation in average ambient air temperature and grain temperature during the storage period (experiment B).
recovery were 79.9, 72.8, and 63.63%, respectively. These values indicated that the quality of rough rice during the storage period was maintained within the first degree criterion.

After drying test B was completed, another storage experiment was conducted using the same grain bin and rough rice as used in drying test B. The average moisture content range of rough rice during the storage period from the middle of October of 1979 to the middle of May 1980 was maintained in the range of 12.5-13.7%, which was a safe moisture content to keep rough rice undamaged. The milling test after the storage experiment showed that brown rice recovery, milling recovery, and head rice recovery were 80, 73, and 64%, respectively. These values indicated that the quality of rough rice during the storage period was maintained within the first degree criterion. No damages due to moulds or insects were found.

Cost Analysis

As discussed in the previous sections, drying and storage of rough rice with the use of a grain bin were found to be highly practical in Korea. In addition to the technical advantages of a grain bin, the economic feasibility must also be considered. However, at present, there are no economically feasible methods that can be compared to drying and storage using a grain bin. The conventional sun drying being practiced in most farm areas, although economically less expensive, has problems of qualitative and quantitative grain damage, frequent operational interruptions because of unexpected bad weather, and difficulty in the mechanization of harvesting. These problems make it difficult for conventional sun drying to be compared to grain bin drying.

Batch or circular dryers were not considered, because only a limited number of them have been supplied. Therefore, in this study, only the drying costs for using a grain bin were calculated. In this experiment, total cost for drying 1 t of rough rice from the initial moisture content (MC) of 20 to 14% was 40,000 won (685 won = U.S.$1.00). The fixed cost was 32,300 won (about 80%) and the variable cost was 7700 won (about 20%). Because the fixed cost took a large portion of the drying cost, the total drying cost can be reduced to less than half when the capacity of the bin is increased to 2 t and the annual use to twice a year. If the price of a bin can be lowered by mass production, the drying cost will be reduced even more. The present drying cost for a circular type of dryer used in farm areas is 600 won per sack of rough rice, which is equivalent to about 12,000 won/t. Therefore, if the additional advantages such as safe storage are considered, a grain bin may be economically reasonable.

Analysis of Solar-Drying Experiments

A solar-drying test of rough rice was conducted at three locations. The same grain bin used in the natural air-drying experiment was also used for solar-heated air-drying experiments. Table 2 shows the results of solar-drying experiments analyzed in this study.

<table>
<thead>
<tr>
<th>Experiment no.</th>
<th>B</th>
<th>C</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity of rough rice (t)</td>
<td>2.0</td>
<td>1.7</td>
<td>2.3</td>
</tr>
<tr>
<td>Amount of air-flow (cm/m²)</td>
<td>4.0</td>
<td>1.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Test period</td>
<td>01/10/78-11/10/78</td>
<td>10/10/78-24/10/78</td>
<td>15/10/79-31/10/79</td>
</tr>
<tr>
<td>Initial moisture content (% wb)</td>
<td>19.8</td>
<td>21.9</td>
<td>25.6</td>
</tr>
<tr>
<td>Average final moisture content (% wb)</td>
<td>13.3</td>
<td>13.7</td>
<td>11.2</td>
</tr>
<tr>
<td>Total fan operation time (hours)</td>
<td>140</td>
<td>130.4</td>
<td>96</td>
</tr>
<tr>
<td>Average drying rate (%/hour)</td>
<td>0.05</td>
<td>0.06</td>
<td>0.15</td>
</tr>
<tr>
<td>Energy consumed per 1% MC reduction (kWh)</td>
<td>7.69</td>
<td>6.29</td>
<td>5.33</td>
</tr>
<tr>
<td>(natural air drying)</td>
<td>(9.70)</td>
<td>(13.64)</td>
<td>(7.54)</td>
</tr>
<tr>
<td>Final moisture content at top layer (% wb)</td>
<td>13.4</td>
<td>15.1</td>
<td>14.4</td>
</tr>
<tr>
<td>Final moisture content at bottom layer (% wb)</td>
<td>12.9</td>
<td>10.2</td>
<td>10.0</td>
</tr>
<tr>
<td>Daily fan operation (hours)</td>
<td>24 hours</td>
<td>8:00-20:30</td>
<td>10:00-17:00</td>
</tr>
</tbody>
</table>
Figure 2 shows the supplementary heating system that was used in Experiment B. It is composed of the flat-plate solar energy collector and heat-storage unit. In this system, the rocks with a volume of 7.2 m³, which were piled over a perforated duct inside the collector, were heated during the daytime, and the heat stored in the rocks was transferred to the drying air during the night. The collectors used in experiment C and E consisted of a clear film cover and a metal black absorber in which an oval cover and flat absorber collector were used in experiment C as shown in Fig. 3 and a flat cover and triangular absorber in experiment E. Because no heat storage unit was provided in these systems, the collectors were only used to heat the air during the daytime.

Performance of Solar Collectors

The performance of the solar collectors used in each experiment was analyzed in terms of temperature rise of drying air and solar collector efficiency. The drying air temperature variations obtained on a typical day with experiment B showed, in general, that the maximum temperature of the air drawn through the rocks occurred at about 14:00 hours and the minimum temperature at about 19:00 hours. Similar patterns of temperature variation appeared throughout the testing period. For the given system, the temperature of the air passing through the perforated duct was increased about 4°C on the average above the ambient air temperature during the night and about 8°C during the daytime.

In experiment C, the temperature rise of air during the solar-drying experiment was in the range of 6.5–21.8°C, and the maximum temperature of drying air was 40.0°C and the minimum was 13.2°C. A similar result of temperature variation appeared in experiment E. The average temperature of air throughout the testing period was 15.3°C, which could reduce the relative humidity from 63.4 to about 40% on the average. The heated air, having such a high drying potential with high temperature and low relative humidity, however, may result in uneven...
drying and overdrying for low-temperature, in-bin drying systems.

The collector efficiency on a typical day in each experiment was calculated from the ratio of the energy collected to the radiation available. The amount of energy collected was based on measurements of the quantity of air and the temperature rise in the air. Calculated efficiencies of the collectors were found to be about 35.0% in experiment B, 46.1% in experiment C, and 43.1% in experiment E.

Solar-Drying Analysis

In this section, moisture variation of grain with electric energy input in the solar-drying experiment is compared with natural air drying. Figure 4 shows the drying curves of grain located at the top, middle, and bottom layers when the heated air was supplied through the solar collector heat storage system in experiment B (Fig. 5 and 6). Throughout the drying period there existed some moisture gradients of the grain at each layer. However, the gradient decreased as drying continued, and the difference in moisture content between the top and bottom layers was less than 2.0% when the grain moisture content (MC_8) reached about 13.3% on the average after 5 days of drying.

The comparison of the average drying curves of natural air drying with and without supplementary heat showed that solar drying gave a much higher rate of drying and required a shorter period of drying to arrive at the desired final moisture content, although it also showed a little greater moisture gradient between top and bottom layers throughout the testing period.

The results of the change in moisture content at each level of the grain mass in experiment E indicated that adding solar energy during the daytime increased the difference in moisture content between the grain at the air inlet and the grain at the air outlet as much as about 12.0%, even though the average grain moisture content reached about 15% after 69 hours of drying operation. It took 96 hours to dry the grain to a safe level for storage of 14.4% at the top layer, but the moisture difference was 4.4% after the completion of drying. The difference in the moisture content between individual layers resulted from high inlet air temperature and low airflow rate. Continued fan operation during the nighttime, when the relative humidity of the ambient air is high, may help in achieving uniform moisture content all over the grain mass.

A similar drying pattern appeared in experiment C in which the fan was operated from 08:00 hours to 20:30 hours, longer than in experiment E. The average moisture content was 13.7%, and the moisture difference between top and bottom layers was about 5.0% at the end of the drying operation. Uneven drying as well as overdrying of the grain was also observed in this experiment.

Energy Requirements

The electric energy requirements for each drying experiment are summarized in Table 3. In general, energy use per kilogram of water removed was lower by as much as 20-50% for solar-heated air drying than for natural air drying. More electric energy was consumed in experiment C when compared to the other two experiments because of its lower airflow rate.

From the analysis, it should be remembered that, under the operational and ambient air conditions examined in experiments B and E, not much saving in energy input as well as advantage in grain drying could be attained by the addition of the solar heating system. However, the need for the solar collector system for grain drying in unfavourable weather conditions should not be underestimated. Therefore, more research must be conducted in the future to develop a supplementary heating system that is applicable to a low-temperature in-storage drying system. There is also a need to decrease the solar collector costs and increase the durability of the collectors.

Fig. 4. Moisture content change of each layer of the rough rice dried with solar-heated air.
### Table 3. Energy requirements per kilogram of water removed.

<table>
<thead>
<tr>
<th></th>
<th>Experiment B</th>
<th></th>
<th>Experiment C</th>
<th></th>
<th>Experiment E</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Natural</td>
<td>Solar</td>
<td>Natural</td>
<td>Solar</td>
<td>Natural</td>
<td>Solar</td>
</tr>
<tr>
<td>Moisture content (% wb)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>20.2</td>
<td>19.8</td>
<td>24.8</td>
<td>21.9</td>
<td>20.0</td>
<td>25.6</td>
</tr>
<tr>
<td>Final (average)</td>
<td>13.6</td>
<td>13.3</td>
<td>15.1</td>
<td>13.7</td>
<td>13.0</td>
<td>11.2</td>
</tr>
<tr>
<td>Total energy consumed (kWh)</td>
<td>64</td>
<td>50</td>
<td>132.3</td>
<td>51.6</td>
<td>52.8</td>
<td>76.8</td>
</tr>
<tr>
<td>kWh/kg of moisture</td>
<td>0.418</td>
<td>0.333</td>
<td>0.678</td>
<td>0.320</td>
<td>0.285</td>
<td>0.206</td>
</tr>
<tr>
<td></td>
<td>(100)</td>
<td>(79.7)</td>
<td>(100)</td>
<td>(47.2)</td>
<td>(100)</td>
<td>(72.3)</td>
</tr>
</tbody>
</table>

*Fig. 5. A solar collector with a heat storage unit used for solar drying (experiment B).*

*Fig. 6. A solar collector without a heat storage unit used for solar drying (experiment C).*
Conclusion

In Korea, there is a great need to improve current grain drying and storage practices at the farm level. With shortages and high prices of fossil fuel, the reduction of energy consumption and the application of solar energy to grain drying are becoming more important.

This study was designed to evaluate the technical feasibility of an in-bin drying and storage system using natural and solar-heated air based on previous experimental results. The following conclusions can be drawn based on the analysis of the experimental results:

• The weather conditions during the drying period (October) of rough rice in Korea were found to have good potential for natural air drying.

• Through natural air drying using a grain bin it was possible to dry rough rice of 1–4 t within 3 weeks to the moisture content necessary for safe storage, and this method also achieved uniform drying.

• In the two storage experiments, the moisture content of rough rice was maintained within 14% wb during the storage period. There was no deterioration in rough rice quality.

• Solar-heated air drying helped in lowering the final moisture content of rough rice and in reducing the drying time and the energy requirements per unit of water removed, compared to natural air drying. Because a high temperature rise of drying air with the solar collectors results in uneven drying and overdrying of rough rice, a low-cost, durable solar collector heat-storage unit should be provided for a low-temperature, in-bin drying system.

• The cost of the in-bin drying system appeared to be higher than that for conventional sun drying. However, in-bin drying has advantages such as prevention from overdrying, preservation of good quality of rough rice, and safe storage. If these advantages are taken into account and the fixed costs of the in-bin drying system can be reduced with an increase in its capacity and the frequency of its annual use, in-bin drying may be economically feasible.

