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Project final report

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2 Executive summary

During the project the following activities were carried out:

Central Mechanical Engineering Research Institute CMERI team:

The statistics of the annual grain production in West Bengal and the other northeastern states of India (Arunachal Pradesh, Assam, Meghalaya, Mizoram, Tripura, Manipur and Nagaland) have been obtained. They included grain and seed production data for paddy, wheat, maize and oilseeds. In West Bengal the total production of paddy rice increased from 14.7 to 15.5 million tonnes whereas the wheat production increased from less than 1 million to more than 1.1 million tonnes between 2003-2004 and 2003-2005. The seed requirement in West Bengal in 2003-04 was 35 thousand tonnes of paddy and 12 thousand tonnes of wheat. In the other northeastern states the demand was 26 thousand tonnes of rice, 41 thousand tonnes of wheat and 5 thousand tonnes of maize seed. Increased demand of seed means increasing demand of mechanical dryers as the safe moisture level for seed storage, 13% wet basis, cannot be maintained under the prevailing climatic conditions without mechanical drying.

The seed production infrastructure has also been surveyed and it was found that there were seven major seed producers (with connections to over 40 state seed farms). Furthermore, the survey has shown that there were 24 major animal feed producers including state owned enterprises in four of the northern states. There are also more than 400 rice mills in West Bengal alone. Finally, there are four major dryer manufacturers in the region.

As a result of the surveys, contacts have been established with nine major seed producing companies as well as with feed mills interested in improving their drying facilities. An important partner is the West Bengal Dept. of Agriculture and especially the seed farm in Burdwan near Durgapur.

The modelling and design work included:

- Determination of thermophysical properties of economically important paddy varieties. They included grain size, density, specific heat, thermal conductivity and sorption isotherms at different temperatures. Mathematical models were fitted to these properties when appropriate.
- Historical data on temperature, humidity and rainfall have been collected for the representative locations of the following regions
- Gangetic West Bengal (Kolkata & Burdwan)
- Sub-Himalayan West Bengal (Jalpaiguri)
- Northeastern States (Guwahati)
- Weather data loggers were placed in the WB Govt. farms at Burdwan, Bankura and Jalpaiguri.

The thermophysical properties of grain and the weather data were added to the existing drying simulation package in order to provide a predictive tool for design and optimisation of in-store drying systems.

In addition to this work, the CMERI team has designed and tested a laboratory-scale two-stage drying system consisting of a fluidised bed dryer and an in-store dryer as 1st and 2nd stage dryers respectively. The fluidised-bed dryer can be operated in batch or continuous mode, has a capacity of 20 kg paddy/h and can remove moisture from 30% down to 20% wet basis. It has been tested within 60-90°C temperature range. The in-store dryer has a capacity of 0.9 m^3 and is using near-ambient air. Drying models have been developed for both dryers.

Full-scale prototypes for both the 1st stage fluidized bed dryer (150 kg/h capacity) and the 2nd stage in-store dryer (4.6 m^3 capacity) have been installed and commissioned at Burdwan seed farm of Govt. of West Bengal. Experiments of the two stage drying system with freshly harvested grains are in progress in order to validate the results of the laboratory tests and to demonstrate the system to users. In addition to research activities, CMERI hosted the 4th Asia Pacific Drying Conference in December 2005 (ADC05) in Kolkata where the principle and applications of the two-stage drying system were demonstrated.

Food Science and Technology, University of New South Wales team

Extensive work on the modelling of two-stage drying of seed of three major grain crops: rice, wheat and maize. The research work included the use of fluidised and spouted-bed dryers and of an in-store dryer using near-ambient air. Seed quality attributes such as viability and vigour are included in the model.

A further major research activity was the development of finite elements method (FEM) to describe the drying behaviour of a single kernel. FEM allows studying the following areas:

- Effect of changes in drying conditions
- Fissuring
- Surface 'melting' effect at high temperature
- Directional drying

Finally, both teams developed training tutorials based on the computer assisted learning principle for dissemination of project outputs among the potential users.

3 Background

Agricultural or natural resource problem targeted by the project

Throughout the developing world, farmers are not reaping the full benefit of the green revolution and the opportunities to earn income from grain surpluses. While profits can be enhanced by increasing production and selling grain when prices are high, the problems remain of poor quality grain that commands low prices and of lack of capacity to store good quality grain until prices are optimal. The introduction of appropriate grain-drying systems is central to the solution of both problems. But this can only be done by involving local industrial partners in research partnerships and improve design and manufacturing options for grain postharvest systems based on locally available materials, while also boosting local expertise for back-up technical support.

Target industries

In South Asia, two grain industry sectors that offer particular opportunities for improving farmer incomes are (a) the production and sale of seed and (b) the supply or use of feed grain products for livestock production. Non-Government Organisations (NGOs) have been active in assisting local farmer groups to take advantage of these opportunities through various co-operative ventures, but a gap remains that will be addressed in this project — to improve local design and manufacture of grain-drying systems and to encourage a systems approach to grain drying and storage.

Wet season storage is a significant problem for both paddy and maize in North India, as well as for oilseeds and pulses, especially crops to be used for seed production. While paddy and wheat are the major staples, maize feed production for livestock (esp. chickens) has increased significantly and aflatoxin contamination has become another serious problem. Well-sealed and aerated storage facilities fitted with second-stage in-store dryers can enable quality maintenance and loss reduction in both seed for planting and grain destined for animal feed.

Improvement of seed drying

While sun drying of seed is still widespread, more reliable and less labour and land intensive systems are needed, by both smallholders and the seed-industry, for both seed drying after harvest and maintenance of low moisture levels during storage, so as to maintain seed viability. Table 1 shows seed requirements and current estimated mechanical-drying requirements for North East India/Bangladesh. The figures for mechanically dried seed are conservative since they represent the government drying sector (around 50%), with the trend being towards an increase in the commercial sector.

Table 1. Seed and mechanical drying requirement for the target area (FAO, 2001)

Crop	**Total quantity of seed produced per year ('000 tonnes)**	**Total requirement of mechanical drying***	
		% of total	('000 tonnes)
Paddy	1,538	10	154**
Wheat	136	20	27
Maize	1.3	75	1

** Represents potential demand for drying system improvement. ** Area in larger market target area (Including Bangladesh). The yearly production of paddy seed in West Bengal is 30 thousand tonnes.*

To reduce risks associated with sun drying, mechanical dryers, generally of small capacity, are being slowly adopted by farmers' groups or drying contractors[1]. However, the major adopters of mechanical dryers, who can play a key role in enhancing benefits to

[1] *NGOs are also active in introducing them.*

smallholders, are the seed-processing companies, feed mills and industrial-scale food processors (e.g. rice, oilseed or pulse mills, soybean-processing plants, flour mills and other industrial users) that require large-capacity equipment. These users represent the leading edge of the industry and are the main clientele for dryer manufacturers.

Animal feed requirements

Aflatoxin contamination is the main challenge for the maize feed industry and drying systems offer opportunities to reduce contaminant risks and improve industry efficiency. Improvements to fluidised-bed technology over the past few years make this the equipment of choice for high moisture grain drying such as in West Bengal. To date, however, no tests have been conducted on local varieties to confirm the suitability of the technology to the region.

Food industry requirements

There is in increasing demand from the food-processing industry for oilseeds such as mustard, sunflower, soybean and groundnuts in NE India. Storage of oilseeds at high moisture content may lead to mouldiness, increase in free fatty acid (FFA), darkening of oil and increase in peroxide value. Food processors are increasingly paying a premium for quality raw materials, especially in NE India.

Improvement of drying systems

The present problems facing the smallholders in West Bengal are similar to those throughout Asia: grain loss after harvest, cost of drying, increased yields from hybridisation creating pressure on the postharvest system, and humid conditions during postharvest handling and storage. These problems have been addressed in other countries in Asia, but utilisation of two-stage, in-store drying has not been adequately assessed in India.

Proposed solution

The two-stage drying system consists of a first-stage involving rapid removal of surface moisture down to about 18% wb using high temperature dryers[2] followed by a second-stage using in-store drying using near ambient air down to the safe storage level of 14% wb or less. The first stage can be conducted on farm, in co-operatives or at grain stores. Second stage drying is usually undertaken at a central storage facility. Two-stage drying will be a key element of this proposal, but since seed is a key target in this project, the use of high temperature will be subject to some limitations. Other forms of first-stage dehydration, such as heat-pump dryers could be alternatives to high-temperature fast dryers.

Thus, the key improvement that this project will deliver for India is a two-stage drying process that allows a split in the drying load between smallholder and village/co-operative level as follows:

1. Many individual farmers or village co-operatives will undertake first-stage drying and then sell their grain to a commercial group. The commercial group will then undertake the second-stage drying that removes more moisture and re-dries the grain during storage as necessary to maintain desired moisture level.
2. Commercial groups can buy undried grain from farmers, bulk it and then undertake first and second-stage drying.

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[2] *Many of the mechanical dryers being introduced in the region could be used for first stage drying but many overheat grain and are not suitable for seed drying. The project will review options and recommend/devise first stage dryers suitable for seed drying.*

3. Co-operatives of farmers may undertake first and second-stage drying and perhaps become seed sellers or millers to capture more profit.
4. Properly dried grain is identifiable and commands a price premium because its advantages are recognised in the key areas targeted by the project (seed, animal feed, and grain for food processors)

Nature/scale of prototype equipment

The prototype equipment will include:

- First stage dryers. They may be flat-bed dryers or high temperature dryers operating in continuous mode (e.g. fluidised or spouted bed). In some cases, a suitable first-stage dryer will already be installed at the test site (i.e. seed store or feed mill) or available from the industry partner. To be considered suitable, the first-stage dryer output capacity will have to match the intake capacity of the second stage dryer, i.e. the throughput per day from first stage dryer will have to be sufficient to fill up the (second stage) in-store dryer. First-stage drying capacity is likely to be of the order of 5–10 tonne/batch for a flat-bed dryer, or 1–5 tonne/h for a fluidised/spouted bed dryer.
- In-store (second-stage) drying system*.* The type and capacity will be selected according to the handling technique, capacity and available storage space. It could be an existing storeroom of a given capacity, or part of a large warehouse with partition walls fitted with ‘in-floor’ or ‘above-the-floor’ aeration ducting, a manifold and an air supply fan with or without a heating system. There will also be provision for a grain-handling system for loading and unloading of grain from the dryer. In practice, for initial prototype testing, a storage facility, with batch capacity of less than 50 tonnes would be used, as in the past experiments in Southeast Asia and China.
- Control equipment. To assure that the system variables conform to the desired values, called reference values (or set points). The control equipment will be required to minimise the energy use and optimise the grain quality.

Users of drying systems

Milling and feed manufacture. There are 400 rice mills in W. Bengal with ca 300 in Burdwan District (CMERI data, 2003). The mills produce polished and parboiled rice, and by-products are used by food processors (rice flour) and feed mills. Per day rice processing per rice mill is 25–30 tonnes. CMERI has also discussed collaboration with Burdwan District Rice Mill Owners Association who have dryers of variable capacity and efficiency in most of their rice mills. The mills are interested in cost-effective and energy-efficient dryers. Feed mills in the region are using mostly maize and some rice by-products. Suitable representatives of this partner group will be involved in the project start-up workshop.

The yearly production of paddy seed in West Bengal is 30 thousand tonnes. Suitable agricultural seed farm in Burdwan District and agricultural seed farms in the district are interested in installing a good drying and storage systems for seeds. The local seed industry in the agricultural seed farm is interested in installing a good drying system for seeds and also a good storing system for the seeds.

Manufacturers of drying systems. West Bengal is among the most industrialised states of NE India and Kolkata (formerly Calcutta) has traditionally played a leading role in the manufacturing in the region (including Bangladesh and Bhutan). Durgapur (where CMERI is located) has large steel mills and provides raw materials for machines manufactured in Kolkata as well as in other parts of India.

Importance of research

This project addresses a prominent gap in regional R&D to improve the postharvest sector. Although results from other different regions of Southeast and East Asia and especially computer models are available for implementation of the proposed project, it is essential to incorporate regional data on crops, weather and socioeconomic conditions. The project will also fine-tune drying models and systems for the specific requirements for seed drying and capitalise on the Indian partners expertise in heat analysis.

4 Objectives

Goal: To improve seed and feed grain quality in order to benefit smallholders in Northeast India.

This goal will be achieved by developing a technically and economically attractive drying and storage system for seed grain crops based on the two-stage drying concept. The objectives of the project are:

1. To scope, develop, test and disseminate improved systems for grain drying
2. To enhance local capacity to design, manufacture and manage grain drying systems which benefit smallholders.

The achievement of these specific components will include:

1. Survey of regional grain drying and manufacturing and selection of industry partner(s).
2. Development of computer-based drying models.
3. Collaborative construction and testing of prototypes in demonstration trials.
4. Training of scientists and manufacturers in the principles and practice of grain dryer design and manufacturing.

5 Methodology

Research methodologies were designed to develop, test and implement appropriate two-stage drying techniques in the seed and animal feed industries, with a primary focus on stage 2 drying for the reasons outlined previously.

Stage 1 drying involves the removal of moisture from grain after harvest down to around 18% wb. This stage can be undertaken on the farm, at a village co-op or at a grain storage facility. The capacity of the first stage dryer can then be set according to the need and first stage drying may also just be sun drying (provided it is conducted with outmost care, i.e. temperature of the grain is monitored, the grain stirred regularly and tempered).

Stage 2 removes moisture from 18% wb down to safe storage level (generally 14% wb). This stage of drying can be performed as ‘in store drying’ and is undertaken at co-operative or commercial level. What is involved is a fan/blower that pushes near-ambient air through the grain (in specially constructed bins or in a warehouse that has been suitably modified). If necessary, supplementary heat (1–5°C above ambient) can be added to ‘gently’ remove moisture. In-store drying removes initial field moisture from 18 to 14% and grain can be aerated regularly as moisture levels creep up again during storage.

The methodology used to complete the different tasks is summarised as follows:

Task: conduct industry surveys.

The grain industry, manufacturers of equipment and main groups of users of drying equipment in Northeastern India were surveyed on the basis of existing statistics, databases and reports, and collaborators sought.

Task: obtaining thermophysical and weather data.

The following grain properties were required in order to develop mathematical drying models: particle density, bulk density, porosity, thermal conductivity, specific heat, sorption isotherms and thin layer drying behaviour (for further details see: Srzednicki et al., 1999). The weather data include air hourly temperature and relative humidity recorded at the key locations where grain drying and storage is taking place.

Task: model development.

Existing drying models were fitted or enhanced (using the deterministic near-equilibrium model that assumes thermal equilibrium without also assuming moisture equilibrium, see Driscoll, 1996). In addition, existing grain quality models (e.g. seed viability) were fitted and modified (see Jittanit et al., 2007). The existing economic models were adapted by inclusion of the local data obtained through surveys of the industry. Ultimately, all these models will be combined into a dryer system model (Driscoll, 1996).

Task: system evaluation.

The dryer system model is using a range of local conditions in order to determine the most suitable option for a given situation. This process enables to define the design parameters required for the development of prototypes.

Task: design.

The design work followed the specifications obtained after the completion of the previous tasks. Standard techniques, especially using computer assisted design packages (current practice at CMERI), were used to accomplish this task.

The systems analysis carried out before the developmental work have determined the capacity and type of dryers most suited to co-operator's requirements. Design activities drew upon the database of designs/models developed in previous work.

Task: conducting pilot tests.

Prototypes were constructed following the design produced in the previous task. There was collaboration between CMERI's mechanical workshops and the equipment manufacturers that were involved in production and commercialisation of the dryers. The prototypes were tested at CMERI with limited quantity of grain. The grain samples were analysed using analytical procedures used in grain testing laboratories. Recommendations were made by the researchers at CMERI in order to optimise the manufacturing and use of equipment.

Task: implementation at a commercial scale.

The feedback of the pilot tests was incorporated into an improved version of the design. The manufacturing and grain industries were involved in the testing process. An economic and technical evaluation based on industry standards lead to the elaboration of final recommendations required for manufacturing and commercialisation of the design.

Task: technology transfer and training.

The information related to the design, operation and the advantages of use of the newly developed dryer systems were disseminated through scientific seminars, in-house training of the partner country personnel as well as short courses for the grain industry. There was intention to include the outputs of the project into 'Grain Storage Tutor' computer-assisted learning package in an intended extension phase of the project.

Task:

There were plans to carry out an economic assessment of project developed technologies using economic models developed in previous projects as well as standard CMERI economic appraisal techniques in an intended extension phase of the project.

Task: preparing the final report

The new proforma introduced by ACIAR in the second half of 2007 was used to produce the final report.

6 Achievements against activities and outputs/milestones

Objective 1: To scope, develop, test and disseminate improved systems for grain drying

no.	activity	outputs/ milestones	completion date	comments
1.1	Surveys and industrial linkages	profiles of industries and manufacturers in the region; data on harvest, quality standards, infrastructure and prices	30/06/2006	PC. Surveys completed and data available. As a result of the surveys, contacts have been established with nine major seed producing companies as well as with feed mills interested in improving their drying facilities. An important partner is the West Bengal Dept. of Agriculture and especially the seed farm in Burdwan near Durgapur
1.2	Modelling and design (Collecting initial data and grain quality studies followed by model fitting)	thermophysical data for main varieties of crops considered by the project	30/06/2006	PC/A Experiments completed and models developed.
1.2	Modelling and design	weather data from the regions obtained and analysed	30/06/2006	PC/A Historical data on temperature, humidity and rainfall have been collected for the representative locations of the following regions Gangetic West Bengal (Kolkata & Burdwan) Sub-Himalayan West Bengal (Jalpaiguri) North-Eastern States (Guwahati) Weather data loggers have been placed in the WB Govt. farms at Burdwan, Bankura and Jalpaiguri for current data recording and analysis later on. The thermophysical properties of grain and the weather data are added to the existing drying simulation package in order to provide a predictive tool for design and optimisation of in-store drying systems.
1.2	Modelling and design	data on quality of seed and maize for animal feed as a function of the drying regime.	30/06/2007	PC/A Data obtained for seed and some extent for maize for animal feed. The latter were to be obtained from areas identified as suitable by the project review panel during the project extension phase. Since the project extension has not been approved, the work on quality of maize for animal feed has been abandoned.

1.2	Modelling and design	development of models capable of testing a range of possible design parameters, demonstrating their advantages and limitations	30/06/2007	PC/A The modelling work has been completed and new parameters incorporated in the existing In-store-drying model (ISD) as well as in the Fluidised bed (FBD) and spouted bed (SBD) drying models. A new model considering drying process in a single kernel has been done using the finite element model (FEM).

PC = partner country, A = Australia

Objective 2: To enhance local capacity to design, manufacture and manage grain drying systems which benefit smallholders

no.	activity	outputs/ milestones	completion date	comments
2.1	Prototype design and testing (model-based systems evaluation followed by design, construction and testing of prototypes)	optimised design parameters	30/06/2006	PC/A The dryer designs (in-store and fluidised bed dryer) were produced by the CMERI team, prototypes build and tested in the laboratory. The control system for the in-store dryer has been has been designed and built at the UNSW, whereas the one for the fluidised bed dryer was designed and built by the CMERI team in Durgapur.
2.1	Prototype design and testing	specifications for design and erection of prototypes	30/06/2006	PC The specifications for the industrial-scale prototypes were developed, the prototypes built and installed at the WB Govt. seed farm in Burdwan.
2.1	Prototype design and testing	financial analysis	31/12/2006	PC The prototypes installed at the seed farm in Burdwan were tested during the wet season harvest of paddy (amon) in 2006. The costs were recorded and assessed. However, the records from several drying seasons would be required for a comprehensive financial analysis.
2.2	Training and dissemination (demonstration trialling and implementation on commercial scale)	cooperation with equipment manufacturers and grain industry established	31/12/2003	PC Initial contacts with the equipment manufacturers and grain industry representatives (government and private) have been established during the introductory seminar conducted on 1-2 December 2003 at CMERI in Durgapur. The seminar was a platform for the introduction of the concept of two-stage drying as for the exchange of information on existing drying technologies for grain
2.2	Training and dissemination	technical and economic assessments	31/12/2005	PC/A A workshop on drying technology was held in Kolkata on 12 December 2005 at the occasion of the 4th Asia-Pacific Drying Conference (ADC2005). The topics included the assessment of technical and economic aspects of the use of two-stage drying for grain.
2.2	Training and dissemination	recommendations on appropriate drying systems	31/12/2007	PC/A A number of papers derived from the project have been published and presented at various conferences.

2.2	Training and dissemination	documentation of the advantages of the new technology	31/12/2006	PC/A Seminar and demonstration of equipment at CMERI in Durgapur on 17th January 2005. An interactive seminar & demonstration program was conducted at CMERI in Durgapur. Different types of dryers developed in CMERI were demonstrated in actual running condition to the participants. The participants included the policy makers i.e. the Govt. agencies, people from food processing industries and also the grassroots users. Utility of two-stage system for grain drying, particularly for seed processing and preservation were explained to the participants. Their opinion was sought regarding the suitability of the dryers and suggestions for modification were taken note of. Another seminar including demonstration of drying equipment was held on 25th September 2006 at the seed farm in Burdwan. The users of equipment discussed their experience with the two-stage drying system.
2.2	Training and dissemination	training modules and trained personnel	30/06/2007	PC/A The results of the research work (thermophysical and weather data) have been included in the drying models that are part of the Grain Drying Tutor. However, the initially planned development of an Indian version of Grain Storage Tutor (Hindi and Bengali versions) that was supposed to take place during the extension phase of the project, had to be abandoned as the latter has not been extended .

PC = partner country, A = Australia

7 Key results and discussion

7.1 Introduction

Throughout the developing world farmers are yet to get full benefit of green revolution. The problems comprise lack of drying and storage facilities and, as a result, poor grain and seed quality. In the entire South Asia near the sea/ocean, quality maintenance and storage, particularly during the wet season, are severe problems for grains like paddy, wheat and maize. While paddy and wheat are major staples, maize is used as feed for livestock. The latter easily suffers from aflatoxin. Conventionally, sun drying is still widely used. Sun drying has problems of low capacity, uncertainties in availability and several hazards. Though mechanical dryers of smaller capacity are being used by farmers’ groups in various locations, larger capacity units are required for major adopters of mechanical dryers/ storage system, seed producing companies, feed mills and feed processors. Drying systems of adequate capacity are rarely available. The problems facing West Bengal and Northeast India which are infested with heavy rain, wet/high humid weather are similar to those throughout South Asia i.e. heavy grain loss after harvest, poor quality, inadequate post harvest processing systems, handling/ storage, humid conditions affecting harvest and quality during storage etc. Although these problems have been addressed in certain countries of South Asia and a range of possible solutions proposed, the utilisation of better technological solution has not yet been implemented adequately.

Northeast India experiences monsoonal rain during harvest of some of its economically most important grain crops (food grain, seeds, raw materials for feeds, oil seeds etc.). Though these harvest crops play a vital role in the region, so far their problems have not been specially focused upon and addressed adequately. The volume of grain production in the recent years is shown in tables 1 and 2.

Table 1. Agricultural Production during 2004-05 in the State of West Bengal

S/N	Crop	Area ('000 ha)	Productivity (kg/ha)	Production ('000 tonnes)
1	Aus	320	2036	653
2	Aman	4086	2500	10215
3	Boro	1400	3300	4620
Total rice		**5806**		**15488**
4	Wheat	470	2426	1140
5	Other cereals	130	1154	150
Total cereals		**6406**		**16778**
6	Pulses	300	850	255
Total food grain		**6706**		**17033**
7	Oilseeds	750	980	735

Source: Evaluation Wing, Directorate of Agriculture, Government of West Bengal

Table 2. Agricultural production in the State of Assam during 2004-05

Crop	Production ('000 Tonnes)
Rice	5276
Wheat	107
Maize	150
Minor cereals and millets	31
Total cereals	5564
Pulses	101
Total food grain	5665
Oilseeds	255

Source: Directorate of Economics and Statistics, Assam, Dept. of Agri., N-E States

The yearly production of seed and crops shown above badly requires systematic, positive and reliable postharvest management systems. West Bengal has been the most important industrialised state in North East India, and Kolkata has traditionally played the leading role of manufacturing in this region (including Bangladesh, Bhutan, Nepal). CMERI being situated at Durgapur near Kolkata amongst industrial/ steel making hub of India is in an advantageous position to deal with the manufacturing of improved drying systems along with scientific/ technological and design investigations and desired solutions.

7.1.1 Research Emphasis

Two stage drying system offers suitable means, advantages for ensuring effective post harvest management of grains/seeds, appropriate drying and storing methods, for maintaining better quality of grains, seeds and feed materials and reducing the problems of aflatoxin and bio-degradation. The key improvement envisaged for India is a two stage drying process that conveniently allows a spilt in the drying load.

The first stage dryers, which are to bring down the moisture level to 18%, may be high temperature continuous fluidised bed or spouted bed. In the second stage in-store dryer, drying is to be done with near ambient air (heated by up to 5 °C above ambient or so, if required) to bring the moisture level to around 14%. This is to be done by intermittent drying as the moisture level of stored grains tends to pick up. The advantage of the two-stage system is the reduction in energy use and associated pollution. Its adoption results in production of good quality grain, seeds and animal feed free of problems of bio-degradation and aflatoxin.

The mechanism has been clearly demonstrated in similar ACIAR projects in collaborating countries (China, Thailand) through introduction of in store drying. The experience gained thereby has been made useful to the present case. The commercial pull/benefits are:

1. In seed and feed sector, industries need to improve the quality (seeds with better germination capabilities and grains/feeds free of aflatoxin and bio-degradation).
2. In the dryer manufacturing sector there is insufficient capacity to assess drying system needs, and supply reliable system components.

There is a growing interest in these aspects among the relevant people/industries which was shown in letters with expression of interest sent by some of them to CMERI.

The research carried out under the current project has devised options for improving existing/new drying systems in general and for West Bengal and neighbouring states in particular, with emphasis on aeration systems, automated controls and minimal supplementary heating, advantages of existing weather for moisture removal from grain, best hours of operation and a suitable management strategy for second stage dryer with support of studies on grain thermo-physical properties, simulation models, local weather records, pilot tests and field trials.

7.1.2 Technical Emphasis

As already mentioned, the first stage dryer is a high temperature continuous dryer (fluidised bed or spouted bed). The second stage in-store dryer should be chosen according to handling technique, capacity and available storage space. This should be supported by suitable control system to conform the operating parameters to the desired ranges.

The project has addressed a prominent gap in regional R&D to improve post harvest sector. Although results of similar projects from other different regions of South-East/East Asia and specially computer models in some form are available for implementation of the project, it was essential to incorporate regional data on crops, weather and socio economic conditions. Furthermore, fine tuning/ improvement in drying models was also necessary and thus needed to be done. Some of the concepts could be adopted from the results of adaptive research work carried out previously in a number of countries of South East Asia/Australia.

Dissemination of project results was a vital point in this project and was carried out in different ways. Those were demonstrations of equipment, workshops and seminars. The initially incorporation (including translation into Bengali and Hindi language) into the existing training package, Grain Storage Tutor package developed under ACIAR and AusAID projects had to take place during the extension phase of the project. This multilingual package is already in use in a number of countries (Thailand, Vietnam, Indonesia and China).

7.1.3 Expected potential benefits

For India and neighbouring countries of South Asia:

- Reduced postharvest losses resulting in higher returns with increased national production of enhanced quality grain, seed and feed.

- Improved nutritional quality of grain and control of aflatoxin leading to reduced risks to livestock and human health.
- Gaining a greater in depth knowledge of basic drying process, analysis, modeling and design.

For Australia:

- Incorporation of drying models for grains, seeds, maize and oil seeds into research work for application to Australian industry.
- Advancement of understanding of heat and mass transfer for bulk drying/storage with emphasis on more efficient use of energy.
- Scientific links with important R&D organisations in South Asia.

Since the seed industries and feed mills are located in rural areas in large numbers, there will be benefits to the people working in the rural sector. Besides, another positive impact will come through reduction in use of chemical grain protectants, optimised energy use and reduction of emissions.

7.1.4 Implementation steps

The achievement of these specific objectives includes:

- Survey of regional grain drying and manufacturing, and selection of industry partners.
- Development/improvement of computer based models.
- Collaborative design/development and testing of prototypes and demonstration trials.
- Training of concerned people on principle and practice of grain dryer design and manufacturing.

7.2 Survey and Industrial Linkages

7.2.1 Survey and information on harvest, quality, infrastructure

Survey has been carried out and information collected on following items:

- Annual grain and seed production data (paddy, wheat, maize and oilseeds) in West Bengal and North-Eastern states
- Safe moisture level of seeds during storage

7.2.2 Grain production

West Bengal

Table 3. Agricultural Production during 2004-05 in the State of West Bengal

S/N	Crop	Area ('000 ha)	Productivity (kg/ha)	Production ('000 tonnes)
1	Aus	320	2036	653
2	Aman	4086	2500	10215
3	Boro	1400	3300	4620
Total rice		**5806**		**15488**
4	Wheat	470	2426	1140
5	Other cereals	130	1154	150
Total cereals		**6406**		**16778**
6	Pulses	300	850	255

Total food grain		**6706**		**17033**
7	Oilseeds	750	980	735
8	Potato	350	25000	8750
9	Vegetables	900	12900	11610
10	Ginger	10	2200	22
11	Turmeric	14	2143	30
12	Red pepper (dry)	65	1077	70
13	Areca nut	10	1900	19
14	Coconut (copra)	25	2000	50
15	Fruits	162	13333	2160

Source: Department of Agriculture, Government of West Bengal

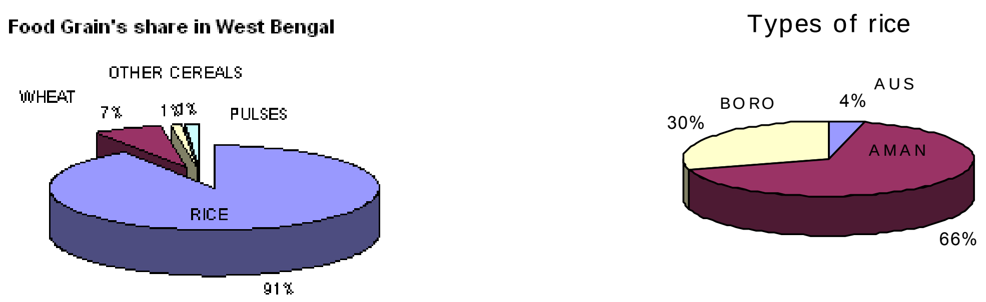


Fig 1. Types of food grain and different varieties of rice in West Bengal

Source: Department of Agriculture, Government of West Bengal

Table 4. Area, Production and Yield Rates of Principal Crops in West Bengal for the year 2003-04. Targets and Achievements (Area in '000 ha, Yield in kg/ha, Production in '000 tonnes)

CROPS	**AREA**		**YIELD**		**PRODUCTION**	
	T	A	T	A	T	A
Aus rice	440.00	339.75	2045	2117	900.00	719.21
Aman rice	4182.60	4126.71	2152	2339	9000.00	9653.58
Boro rice	1378.00	13990.15	3301	3086	4550.00	4289.46
Total rice	6000.60	5856.61			14450.00	14662.24
Wheat	430.00	425.72	2442	2315	1050.00	985.69
Pulses	316.00	251.86	949	840	300.00	211.64
Total food grains	6746.6	6534.19			15800.00	15859.57
Oil seeds	580.00	665.00	846	928	490.75	612.00
Potato	315.00	308.43	22500	24711	7087.50	7621.64
Vegetables (excluding potato)	850.00	850.00	12200	13000	10370.00	11050.00
Fruit		155.00		13000		2015.00

Source: Department of Agriculture, Government of West Bengal.

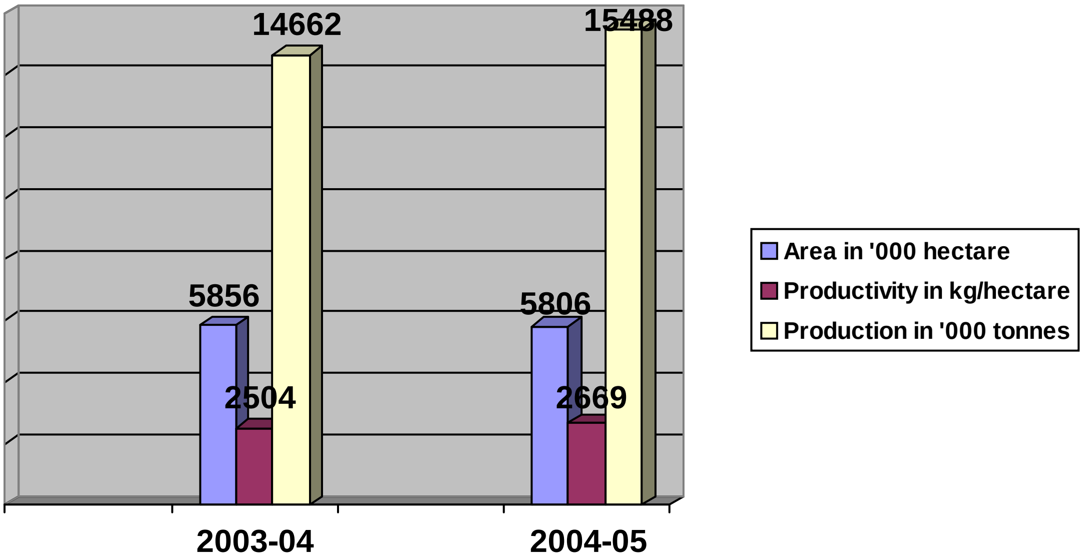


Fig 2. Rice Production in West Bengal

Source: Department of Agriculture, Government of West Bengal

Northeastern States

Table 5. Total Food Grain Production in North-Eastern Region as in 2001 (in '000 tonnes)

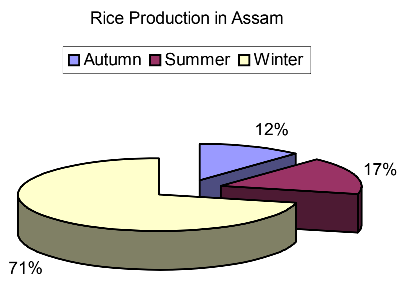
Rice	Maize	Wheat	Millet	Jowar	Bajra	Ragi	Barley	Total food grain
5464.10	237.00	107.00	38.90	1.70	1.70	3.60	6.40	5860.4

Source: Draft Report of the Task force on Development Initiatives for the NER, Sept. 2005

Table 6. Agricultural Production in North-Eastern Region (in '000 tonnes)

Crop	Arunachal Pradesh (2004-05)	Assam (2002-03)	Meghalaya (2004-05)	Mizoram (2002-03)	Tripura (2004-05)	Manipur (2001-02)	Nagaland (2000-01)
Rice	161	3738	160.4	109.3 (Jhum rice: 67.1)	571.7	438.8	30.11
Wheat	7.8	78	9.9		1.9	2	
Maize	65	14	42	1.5		26.3	1.3
Minor cereals and millets	22.5 (Millet)	5.5	2.3 (Small millets)				0.7 (Bajra)
Total cereals	256.3	3834	214.6			465	
Pulses	10	60	5.4	5.0	5.0	15.2	0.1
Total food grains	266.3	3894	220.1			482.3	
Oilseeds	34	191	9.7	2.2	2.7	14.9	
Potato	43			3.6	93.5	57.8	
Ginger	43			46.7			
Chilli	2.8						
Sugarcane	22	916			50.4	172.7	
Vegetables	47			39.9			25.3 (Tubers)
Turmeric	2.3						

Source: Directorate of Economics & Statistics, Assam, Dept. of Agriculture, N-E States



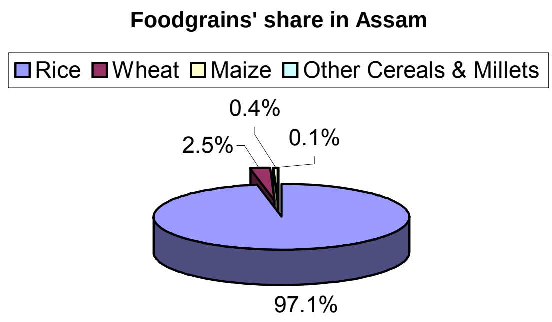


Fig 3. Types of food grain and different varieties of rice in Assam

Source: Directorate of Economics & Statistics, Assam, Dept. of Agriculture, N-E States

7.2.3 Seed production and quality

The seed requirement (quantity and quality) is as follows:

Table 7. Seed requirement of West Bengal (in '000 tonnes) for the year 2003

Crop	Seed Required	Processed Seed, Available	Method of Processing	Percentage Germination
Rice	35.0	25.2 (Kharif) 5.0 (Ravi)	By processing plant & by semi-mechanised method	80 %
Wheat	12.0	10.0	- Do -	85 %
Maize	0.2	0.18	- Do -	80 %
Mustard/Rape Seed	0.7	0.7	- Do -	85 %

Source: Office of the Chief Seed Certification Officer, Govt. of West Bengal

Table 8. Quality requirement for seed

Crop	Harvested moisture	Seed moisture required (% wet basis)
Paddy, Wheat and Maize	20-25 %	13 %, 12 % and 10 % respectively
Mustard	14-16 %	8 %
Pulses		9 %

Source: Office of the Chief Seed Certification Officer, Govt. of West Bengal

Table 9. Seed requirement of North-East States (in '000 tonnes) for the years 2004-05

State	Rice	Wheat	Maize	Pulses	Oil Seed
Assam	24.3	40.6	1.0	8.7	2.1
Arunachal Pradesh	1.3	0.3	3.3		
Meghalaya	1.8	0.4	1.6		
Mizoram	0.8 (0.6 Jhum rice)		0.7		

Source: Dept. of Agriculture, Assam and North-East States

Table 10. Seed moisture content and seed storability

Seed moisture content (% wet basis)	Effect on seed
35-80	Moisture content of developing seed, not matured enough for harvest
33-60	Seeds germinate when they imbibe water to these levels
18-40	Seed physiologically mature, respiratory rate high, susceptible o field deterioration, heating occurs if seed bulked without adequate ventilation, moulds and insects very active. Seed susceptible to mechanical damage in harvesting and handling
13-18	Respiratory rate still high, can get heated at a higher level; moulds and insects can be damaging, seed resistant to mechanical damage

10-13	Respiratory rate still high, can get heated at a higher level; moulds and insects can be damaging, seed resistant to mechanical damage
10-13	Seed stores reasonably well for 6 to 18 months in temperate climate; insect can still be a problem, seed susceptible to mechanical damage
8-10	Seed sufficiently dry for 1 to 3 years' storage at temperate climate; very little insect activity. Seed very susceptible to mechanical damage
4-8	Safe moisture content for sealed storage
0-4	Extreme dessication can be damaging to seed; hardseededness develops in some kinds of seed

Source: Office of the Chief Seed Certification Officer, Govt. of West Bengal

The rate of deterioration of crop seed in storage increases as seed moisture content increases. Mature seeds are hygroscopic; their moisture content will vary with the relative humidity of the atmosphere. Equilibrium moisture content varies among different kinds of seeds. In general the equilibrium moisture content of oily seed is lower than that of starchy seeds at the same relative humidity and temperature.

Temperature also plays an important role in the life of seed. Within the normal range, there is increased biological activity of seed, insects and moulds as temperature rises. In bulk stored seed at high moisture content, metabolic activity of seed and associated micro-organisms produces heat which raises the temperature of the seed mass. The increase in temperature accelerates biological activity which causes further heat production and may completely kill the seed.

Temperature below 10^0 C is effective in maintaining seed quality even though relative humidity may be relatively high. Seed moisture content may increase during such storage but the low temperature will reduce the adverse effects. Removing high moisture seed from cold storage can be done safely, however, is a complicated operation. As soon as seeds are removed from cold storage, moisture will condense on the surface of the seed. Seed moisture content will then increase to even higher levels.

While both seed moisture content and temperature are important factors in seed storage, moisture content has greater direct influence on seed longevity. Very dry seed will store well at temperature up to 32 ^{0}C. The rule of thumb is that 1% decrease in moisture content or 10 ^{0}C decrease in temperature nearly doubles storage potential of seed.

7.2.4 Infrastructure

Infrastructure of seed /feed producers, dryer manufacturers, rice mills in West Bengal and feed industries in North-East States are mentioned below:

West Bengal

Seed Producers

- State seed farms
- Universities
- M/s Annapurna Seeds
- M/s Arambag Seed Farm
- M/s Pallishree Ltd.
- M/s ITC Limited
- M/s Taraknath seed

Feed Industry

- Amrit Feeds Ltd.
- Animal Feeds & Fodders Mills (P) Ltd.
- Arambagh Hatcheries Ltd.
- Godrej Agrovet Ltd.
- Goldmohur Foods & Feeds Ltd. (Hindustan Lever)
- Government of West Bengal
- Harekrishna Fodder Mills Pvt. Ltd.
- Himalayan Feed Manufacturing Co (P) Ltd.
- Induss Feeds
- Modern Feeds
- North Bengal Feed Industries
- Premier Feeds Company Pvt Ltd.
- Shalimar Food Products
- Shibshakti Agro (India) Ltd.
- Shreekrishna Fodder Mills Ltd.
- Uni Cattle & Poultry Feeds Pvt. Ltd.

Drying Equipment Manufacturers

- SKD Combustion & Engineering Co
- Induss Food Food Products &Equipment Ltd.
- Damodar Process Plant Pvt. Ltd.
- Andrew Yule & Co Ltd

Rice Mills

There are around 400 rice mills in West Bengal having total yearly production of 2.4 million tonnes.

North East States

Seed industry

Assam

- Number of seed farms of Agriculture Department: 41

Feed Industries of North-East States

Assam

- Delux Feed Products (P) Ltd.
- Eastern Manufacturing Company
- Government of Assam

Manipur

- B S Animal Feeds Corporation (P) Ltd.
- Government of Manipur

- Yumsha Feed Products

Meghalaya

- Government of Meghalaya
- Premier Feed Mill

7.2.5 Industries and industrial linkages

Identification of suitable industrial partner

- Visited and interacted with several grain /seed and feed industries. Important among them are M/s Premier Feeds Limited, M/s Arambag Hatcheries Ltd., M/s Modern Feeds, M/s Induss Food Products & Equipments Ltd., M/s Annapurna Seeds and M/s Pallishree Limited.
- M/s Pallishree Ltd., M/s Annapurna Seeds and M/s Sree Durga Rice Mill have expressed interest in cost effective and improved seed dryer /seed drying system.

Close contacts have also been established with Department of Agriculture, Govt. of West Bengal.

Linkages have been established with Dept. of Agriculture, Govt. of West Bengal, which is interested in setting up improved grain drying and storage facility as envisaged. Necessary facilities have been provided at Burdwan seed farm for installation of the prototype for experimentation and relevant studies.

After satisfactory experiments at Burdwan seed farm, when the system is set ok, the drying/storing system is likely to be installed in other farms of Govt. of WB such as in North Bengal (Dhupguri), Murshidabad, Midnapore etc. which would involve covering of different climatic conditions.

The state government officials informed the project team that there is a serious requirement for proper drying/storing of wheat seed and also pulses' seeds, which are required to be stored for one year including the rainy season. These aspects also could be covered by the dryer and storage system being developed and should be tried.

Meetings were held with Dr. Dhabaleswar Konar, Director of Agriculture & Ex-officio Secretary. Mr. Subir Choudhury, Chief Seed Certification Officer, Dr. Paritosh Bhattacharjee, Chief Agronomist and other officials of Dept. of Agriculture, Govt. of West Bengal.

Data have also been collected on production, seed holding capacity, existing drying practice, requirement of dryer etc by different industries, which are shown in details below.

Survey and Data Collection	
Feed Industry	
1. Name:	M/s Premier Feeds
Address:	12, Amir Ali Avenue, Kolkata- 700 017
Tel/Fax/E-mail:	Tel: 033-25647579
2. Profile:	
(Business Interest/Turnover)	Poultry /Cattle /Pig Feed; Rs. 1 Crore (107)
3. Production Rate:	10 tonnes / day
4. Seed holding / stock time:	<10 day
5. Existing Drying Practice:	Sun drying

6. Moisture reduction before processing:	10-18 %
7. Dryer requirement:	Useful for such feed company
8. Suitable Dryer Size	Up to 5 tonnes /h

Survey and Data Collection	
Feed Industry	
1. Name:	M/s Arambag Hatcheries Ltd.
Address:	Feed Plant, Ilambazar, Birbhum
2. Profile:	
(Business Interest/Turnover)	Poultry Feed
3. Production Rate:	300-350 tonnes / day
4. Feed ingredients	Maize: 55-60 % Deoiled Soybean & Groundnut: 25-30 % Fish Meal, Bone Meal: 10-15 % Vitamins, Minerals Antioxidants, Enzymes: 0.5-1 %
5. Feed Price:	Rs. 10-11 / kg
6. Total monthly poultry feed production of Arambag Hatcheries Ltd:	Ilambazar 7000 t Arambag 3000 t Bakreswar 1000 t Siliguri 1000 t Total 12000 t

Survey and Data Collection	
Feed Industry	
1. Name:	M/s Modern Feeds
Address:	52A, Shakespeare Sarani, Chandan Niketan, Kolkata- 700 017
Tel/Fax/E-mail:	Tel: 033-22872044/55; fax: 22816990
2. Profile:	
(Business Interest/Turnover)	Poultry Feed; Rs. 30 Crore (3 107)
3. Production Rate:	100 tonnes / day
4. Seed holding / stock time:	7 – 10 days
5. Existing Drying Practice:	Sun drying
7. Dryer requirement:	For the time being not required; will add to the cost of feed

Survey and Data Collection	
Feed Industry	
1. Name:	M/s Induss Food Products & Equipment Ltd.
Address:	238/B, A J C Bose Road, Kolkata- 700 020
Tel/Fax/E-mail:	Tele: 033-2247-1962/9266; Fax: 2247-1874
2. Profile:	
(Business Interest/Turnover)	Cattle feed, manufacturer of paddy parboiling drying plant; Rs. 40 Crore (4 107)
3. Production Rate:	Animal feed: 50 tonnes / day (Maize 60%, Soybean 25-30%)
4. Seed holding / stock time:	4-5 days (of raw materials)
5. Existing Drying Practice:	Mechanical dryers/Field drying
6. Moisture reduction before processing:	14 - 32 %
7. Dryer requirement:	Useful for the operations of the company
8. Suitable Dryer Size	8 - 50 tonnes per batch

Survey and Data Collection	
Seed Industry	
1. Name:	M/s Annapurna Seeds
Address:	2, N. C. Dutta Sarani, Suite No. 15, 2nd Floor, Kolkata - 700 001
Tel/Fax/E-mail:	Tele: 033-22107849
2. Profile:	
(Business Interest/Turnover)	Paddy / Vegetables; \1 crore (107)
3. Production Rate:	Paddy: 4000 t/y Vegetable Seed : 10 t/y
4. Seed holding / stock time:	6 months
5. Existing Drying Practice:	Sun drying / Dehumidified air
6. Moisture reduction before processing:	Cost effective solar dryer
7. Dryer requirement:	Cost effective solar dryer
8. Suitable Dryer Size	2 t/h

Survey and Data Collection for the year 2003			
Seed Industry			
Pallishree Ltd., Sal Lake City, Kolkata –700 064			
Crop	Seed Production (in tonnes)	Method of Processing	Germination Quality
Paddy	18000	Sun-drying	As per Seed Act
Wheat	500	Sun-drying	- do -
Pulses (Moong, Lentil, Gram, Kalai etc.)	60	Sun-drying	- do -
Mustard/Rape Seed	50	Sun-drying	- do -

7.3 Modelling and Design

7.3.1 Grain Thermophysical Data

- Thermophysical properties; dimensions, density, specific heat, thermal conductivity for local varieties of grains have been evaluated by experimental measurements. Experiments have also been conducted to determine the sorption isotherms.
- Some available empirical relations of the above properties with moisture content have also been collected.
- Some data of sorption isotherms at different temperatures and relative humidity have been obtained from available sources and also by experimentation.

Table 11. Physical dimensions of local varieties of paddy

Variety No	Length (mm)	Average Length	Width (mm)	Average Width	Thickness (mm)	Average Thickness
1	8.99 9.78 9.41 8.73 8.74	9.13	2.16 2.16 1.92 1.96 2.17	2.07	1.74 1.78 1.79 1.69 1.34	1.67

2	10.07 10.78 9.54 9.94 9.99	10.06	2.59 2.59 2.69 2.58 2.67	2.62	1.82 1.91 1.78 1.97 1.67	1.83
3	7.63 8.26 8.22 7.94 8.19	8.05	2.63 2.21 2.36 2.57 2.46	2.45	1.68 1.72 1.78 1.64 1.64	1.69
4	8.02 8.51 7.35 7.60 7.58	7.81	2.66 2.76 2.63 2.56 2.77	2.68	1.89 1.90 1.88 1.54 1.89	1.82

Measurement of Bulk Density

The measurements were carried out at three moisture contents [~14% wet basis (wb), ~20%wb and ~ 27%wb] for all four varieties. An example of the values obtained for the variety No. 4 is show in Table 12.

Table 12. Measurement of bulk density

Variety No.: 04; Moisture Content: 14.5 %

Serial No.	Volume(cm3)	Total Weight(g)	Container Weight(g)	Bulk Density(g/cm3)	Average Bulk Density(g/cm3)
1	250	182.38	25.04	0.6293	0.625
2	200	148.78	25.07	0.6185	
3	100	87.78	25.06	0.6272	

The variation of bulk density with moisture content for the short and long grain paddy varieties is shown in Figure 4.

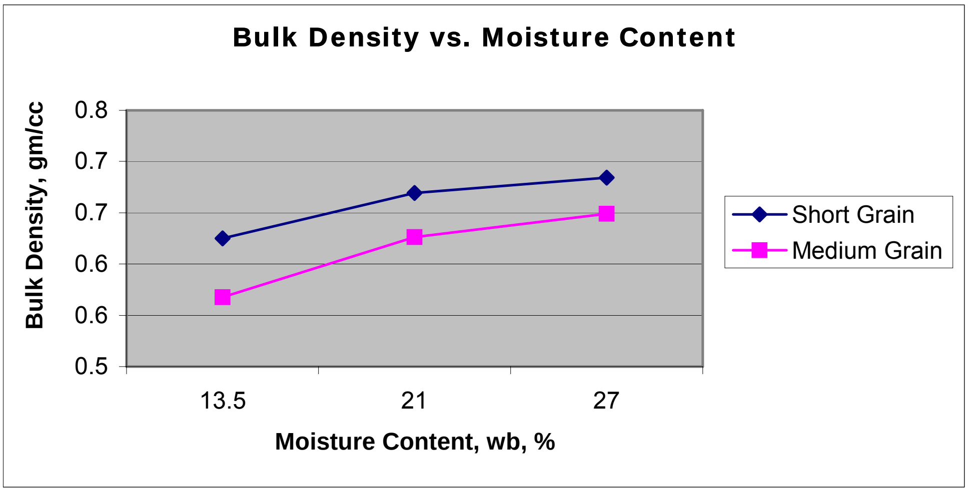


Fig 4. Variation of bulk density of paddy with moisture

Measurement of Thermal Properties

The measurements were carried out at three moisture contents [~14% wet basis (wb), ~20%wb and ~ 27%wb] for all four varieties. An example of the values obtained for the variety No. 4 is shown in Table 13.

(Instrument : Quick Line–30, Anter Corporation, Probe: 00020018)

Sample No.: 04
Moisture Content: 14.5 %
Heater: 24 % ON
Initial Temperature: 24.4 ^{o}C
Temperature at 50%: 29.6 ^{o}C
Average Temperature at which the properties were determined: 27.01 ^{0}C

Table 13. Thermal properties of the rice variety No 4

Property	Value
Bulk Thermal Conductivity	0.104 W /m.K
Volume Heat Capacity	0.494 x 106 J /m3.K
Thermal Diffusivity	0.211 x 10-6 m2 /s

Some Empirical Relations on Thermophysical Properties of Paddy

Physical Properties

Length: L = (a + bM) mm; M = Moisture content (%, wet basis)
Short grain: a=7.318, b=1.22*10^{-2}
Medium grain: a=7.747, b=1.27*10^{-2}
Long grain: a=8.941, b=5.84*10^{-2}
Width: W = (a + bM) mm
Short grain: a=3.358, b=8.90*10^{-3}
Medium grain: a=2.842, b=7.62*10^{-3}
Long grain: a=2.388, b=1.65*10^{-2}
Thickness: Thick = (a + bM) mm
Short grain: a=2.287, b=8.90*10^{-3}
Medium grain: a=1.842, b=8.90*10^{-3}
Long grain: a=1.765, b=1.43*10^{-3}

Kernel Volume:
Medium grain: V = (9.7339 + 0.5097M)10^{-5} m^{3}; M = Moisture content (%, wet basis)
Long grain: V = (15.4038 + 0.2994M)10^{-5} m^{3}
True Density: 1027 – 1405 kg/m3
Long grain: d_t = 1046.1 – 1.01M kg/m^{3}; M = Moisture content: 14-22 %, wet basis

Bulk Density:
Short grain: d_b = 537.6 + 1.22M kg/m^{3}; M = Moisture content: 14-22 %, wet basis
Medium grain: d_b = 567.2 + 4.13M kg/m^{3}; M = Moisture content: 06-28 %, wet basis
Long grain: d_b = 529.2 - 1.105M + 0.00955M^{2} kg/m^{3};
M = Moisture content: 14-22 %, wet basis
Porosity: 46 – 60 %

Short grain: P= 49.7 – 0.227M %; M = Moisture content: 14-22 %, wet basis
Short grain: P= 65.6 – 0.475M %; M = Moisture content: 12-18 %, wet basis
Long grain: P= 49.4 + 0.064M - 0.0099M^{2} %;
M = Moisture content: 14-22 %, wet basis

Thermal Properties

Specific heat: 1.3 – 2 kJ/kg K
Short grain: c_p = 1.269 + 0.03489M kJ/kg K;
M = Moisture content: 11-24 %, wet basis
Medium grain: c_p = 0.9214 + 0.0545M kJ/kg K;
M = Moisture content: 10-20 %, wet basis

Medium grain: $c_p = 1.620 + 0.03114M$ kJ/kg K (Bala, 1997)
M = Moisture content: 9.76-30 %, wet basis
Bulk Thermal Diffusivity: 0.0003600 – 0.0003852 m^2/h
Ref: Bala B K, 1997 "Drying and storage of cereal grains" , Oxford and IBH Publishing Co., New Delhi
Short grain: $k_d = 0.000451 - 0.00000585M$ m^2/h;
M = Moisture content: 10-20 %, wet basis
Medium grain: $k_d = 0.000468 + 0.00000897M$ m^2/h;
M = Moisture content: 10-20 %, wet basis
Thermal Conductivity: 0.1021 – 0.1270 W/m K
Short grain: $k = 0.1 + 0.00111M$ W/m K;
M = Moisture content: 11-24 %, wet basis
Medium grain: $k = 0.0866 + 0.00133M$ W/m K;
M = Moisture content: 10-20 %, wet basis

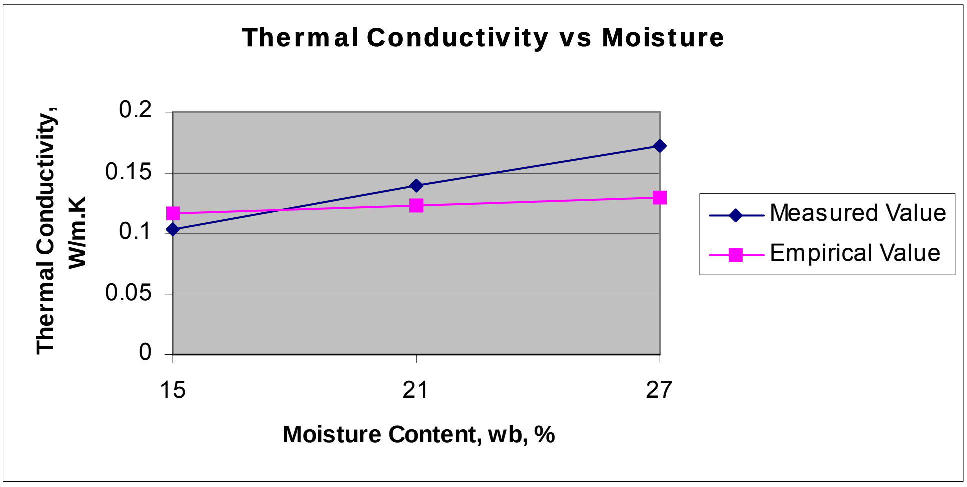


Fig 5. Variation of thermal conductivity of paddy with moisture

Sorption Isotherms

Sorption characteristics of local paddy have been determined in an environmental test chamber with an operating temperature and relative humidity range of 100 C – 600 C and 10% - 95% respectively. The moisture content of paddy was measured with a digital capacitive type moisture meter with an operating range of 0-30%.

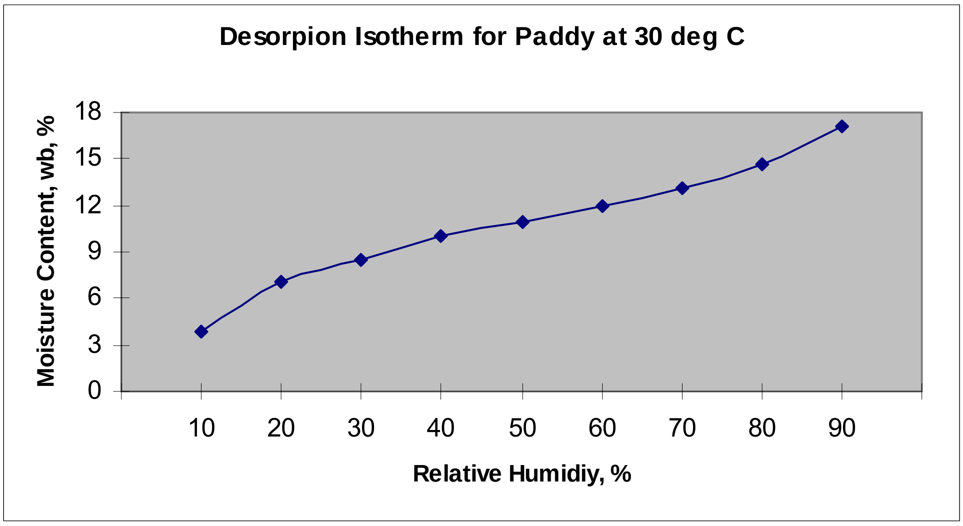


Fig 6. Desorption isotherm

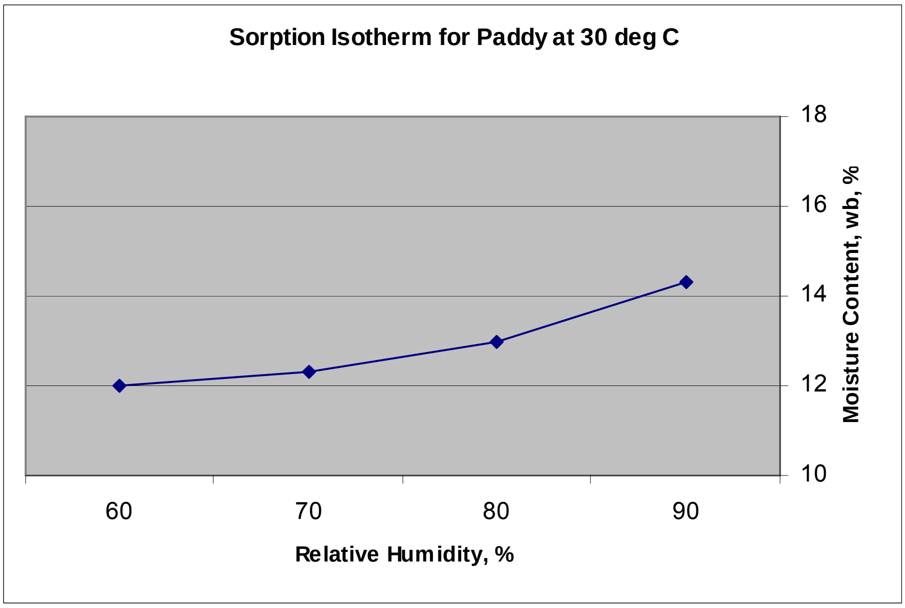


Fig 7. Sorption isotherm

7.3.2 Weather Data

- Historical data on temperature, relative humidity and rainfall have been collected for the representative locations of the following regions:
  - Gangetic West Bengal (Kolkata & Burdwan)
  - Sub-Himalayan West Bengal (Jalpaiguri)
  - North-Eastern States (Guwahati)
- Weather data loggers have been placed in the WB Govt. farms at Burdwan, Bankura and Jalpaiguri for current data recording and analysis later on. These weather recordings are on-going.

Table 14 a. Temperature data for Sub-Himalayan West Bengal

Month	Average Daily Maximum		Highest Maximum		Average Daily Minimum		Lowest Minimum	
	From	To	From	To	From	To	From	To
July 1998	18.8	32.4	19.8	36.0	15.1	25.7	13.8	24.0
August 1998	18.5	31.8	20.1	35.0	14.9	25.9	13.2	23.7
September 1998	19.4	32.8	24.0	36.3	15.0	25.5	12.9	24.0
October 1998	18.7	32.1	21.5	37.0	12.9	25.1	10.0	21.5
November 1998	18.6	30.4	21.4	33.0	8.5	18.9	6.3	15.5
December 1998	17.1	28.2	19.5	30.6	5.4	12.6	2.8	10.0
January 1999	12.7	25.6	14.8	28.5	2.7	10.7	1.0	9.9
February 1999	15.7	30.0	18.6	33.1	6.4	14.7	3.1	12.2
March 1999	18.1	33.8	19.7	36.5	8.5	16.0	6.5	13.6
April 1999	20.1	36.1	22.0	40.8	12.0	23.7	9.3	15.6
May 1999	18.8	33.3	21.2	37.8	11.2	23.7	8.5	21.6
June 1999	22.3	33.5	23.0	39.4	13.3	24.8	11.4	21.8

Source: Dept. of Agriculture (Agr. Met. Section, Writers' Buildings) West Bengal

Table 14 b. Temperature data for Gangetic West Bengal

Month	Average Daily Maximum		Highest Maximum		Average Daily Minimum		Lowest Minimum	
	From	To	From	To	From	To	From	To
July 1998	31.8	34.5	33.6	37.2	23.1	27.1	21.0	25.0
August 1998	31.2	33.4	33.3	35.4	24.6	27.0	21.2	25.4
September 1998	31.0	32.8	33.1	37.6	22.4	26.3	24.4	28.0
October 1998	31.2	32.8	34.1	36.5	23.0	25.4	18.0	22.6
November 1998	28.1	31.7	31.1	33.1	17.5	21.4	9.5	16.5
December 1998	26.0	27.7	28.0	30.7	10.5	14.2	6.9	10.8
January 1999	24.4	26.3	28.8	31.8	9.0	12.2	6.5	9.5
February 1999	28.8	31.8	32.0	36.4	12.5	16.7	8.0	12.2
March 1999	31.3	37.0	36.1	41.1	16.4	22.4	13.4	16.3
April 1999	32.4	41.1	34.3	45.0	24.2	27.1	18.0	23.5
May 1999	33.2	35.8	36.0	44.0	23.2	26.1	19.8	21.7
June 1999	31.8	34.6	35.1	41.2	24.1	26.4	21.1	24.8

Source: Dept. of Agr. (Agr. Met. Section, Writers' Buildings) West Bengal

Table 15. Rainfall in mm in various districts of West Bengal

District	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Darjeeling	997	928	352	131	12	0	3	0	1	42	274	695
Jalpaiguri	1169	1296	538	160	15	0	2	0	8	167	394	590
Coochbehar	935	855	789	283	0	0	0	0	5	174	311	523
Dinajpur (N)	943	719	519	234	2	0	0	0	5	22	221	393
Dinajpur (S)	615	440	460	303	1	0	0	0	0	90	212	248
Malda	540	323	409	277	17	0	0	0	0	13	130	332
Murshidabad	434	295	294	220	28	0	0	0	0	24	135	253
Nadia	301	227	160	108	109	0	0	0	0	20	119	198
24-Pargs.(N)	354	261	197	127	177	0	0	0	0	5	165	172
24-Pargs.(S)	269	254	515	197	244	0	0	0	0	1	240	221
Howrah	230	337	337	178	126	0	0	0	0	4	241	190
Hooghly	263	151	207	110	114	0	0	0	0	1	152	264
Burdwan	278	251	188	92	59	0	0	0	0	15	185	321
Birbhum	386	392	269	260	16	0	0	0	0	13	161	320
Bankura	257	171	200	213	21	0	0	0	0	1	210	248
Purulia	248	203	232	155	26	0	0	0	0	0	167	213
Midnapur (W)	226	87	228	133	47	0	0	0	0	5	257	154
Midnapur (E)	175	130	493	268	118	0	0	0	0	2	228	229

Source: Dept. of Agriculture (Agr. Met. Section, Writers' Buildings) West Bengal

7.3.3 System evaluation for drying system

If drying is performed at a very high rate, the grain becomes susceptible to fissuring, due to the development of temperature and moisture gradients within the product. Fast dryers operate at higher temperatures, and will tend to cause fissuring if the grain is not allowed to temper. For paddy, once the moisture is reduced below a certain moisture level (about 18%, moisture content corresponding to a significant drop in water activity below 1), high temperature drying becomes inefficient and will tend to induce cracking.

To avoid this and to achieve higher energy efficiency, drying in two stages have been developed around the world. The basic strategy is to use high temperatures while the grain is still elastic and contains high moisture, and low temperatures for removing bound water from the product so that large stresses are not developed and easy stress relaxation within the product is possible.

The two-stage drying system consists of a first-stage involving rapid removal of surface moisture down to about 18% wb using high temperature dryers followed by a second-stage drying using near ambient air down to the safe storage level of 14% wb or less. Lab-scale units of 1st stage fluidised bed dryer and 2nd stage in-store dryer have been developed and installed at CMERI. Experiments have been conducted on lab-scale units for system evaluation and parameter optimisation.

Fluidised Bed Drying

The Fluidisation Process

Fluidisation is the process of interaction of fluid with solid particles by which the later is brought to a state of fluid like behaviour. When a fluid passes upward through a bed of particles the fluid initially percolates through the void space between the particles. With an increase in flow velocity, particles tend to vibrate and move apart. At still higher velocity, a situation is reached when the particles are all just suspended in the upward flowing fluid. At this condition the frictional drag force on the particle by the fluid counter balances the weight of the particle with compressive action on the particle disappearing as the pressure drop across any portion being equal to the weight of particles and fluid in that portion. The bed of particles is then just fluidised and is referred to as incipiently fluidised or at minimum fluidisation.

A further increase of flow velocity usually results in progressive smooth expansion of the bed with appearance of bubbles. At higher flow velocities, however, the agitations due to bubbling and channelling of gas become more violent. The bed does not expand much beyond its volume at minimum fluidisation and it is called a bubbling fluidised bed (see Fig. 8).

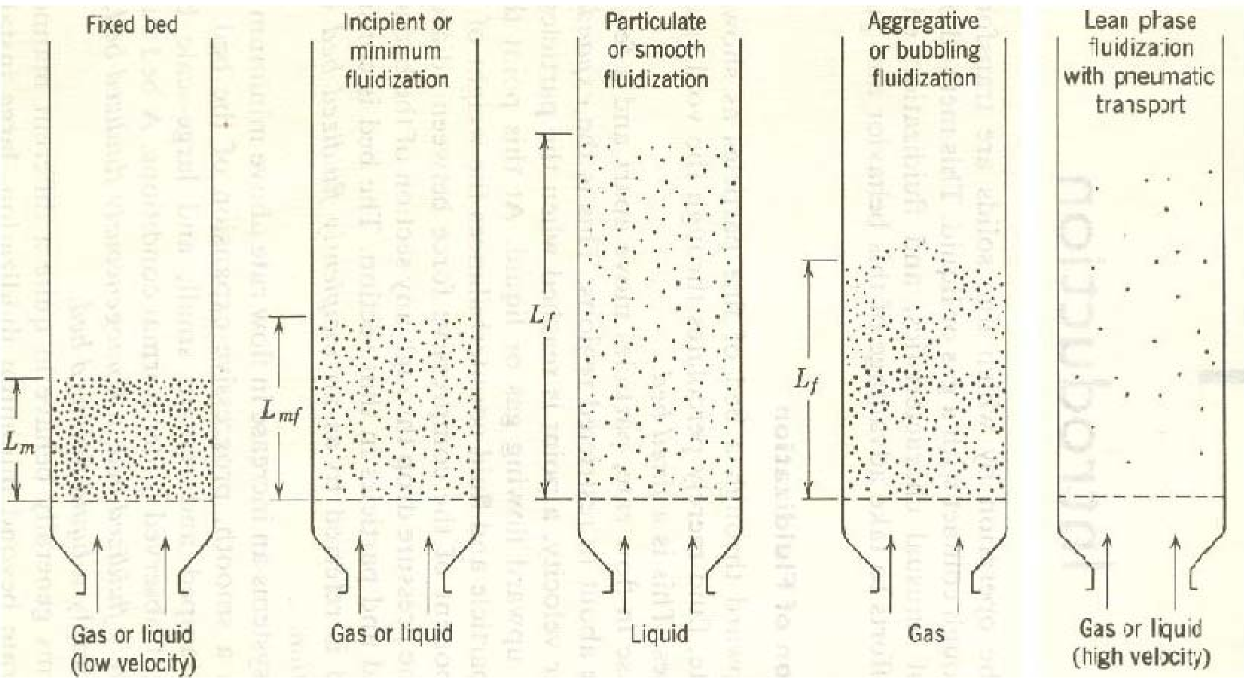


Fig. 8. Different phases of fluidisation in a fluidised bed

Source: Mathur and Epstein (1974)

Drying in a fluidised bed

As in other process applications fluidised bed system has been used in drying process also and fluidised bed drying technique holds an important position among modern drying methods. In the fluidised bed (FB) dryer drying is based on passing hot air through the bed of particulate materials supported on a gas distributor. Fluidised bed dryers can be either batch or continuous types. The former is usually for small scale of production. For larger scale of production continuous dryers are mostly used. The dryer dimensions mainly depend on:

- Throughput of the material to be dried
- Mass of moisture to be removed
- Gas velocity
- Material residence time in the dryer

When the hot gas (drying agent) is supplied at a velocity higher than the terminal velocity of the wet solid, the drying of the wet solid occurs in a suspended or fluidised state. This phenomenon is known as fluidised bed drying.

Fluidised bed dryers are used extensively for the drying of wet particulate and granular materials that can be fluidised.

In fluidised bed drying the process is carried out in a bed fluidised by the drying medium. The drying medium is introduced through the grid, which enables it to be distributed more evenly over the cross-section of the dryer. The intimate interaction between the drying gas and the fluidised particles induce higher heat and mass exchange leading to effective drying.

Advantages of fluidised bed drying

- High Drying Rate
- Higher Thermal Efficiency
- Uniformity in temperature and moisture content for the particulates
- Easy Material Transport
- Ease of Control
- Low Maintenance Cost
- Suitable for Small as well as Large Scale Operation

Fluidised bed dryer can be designed and used for any scale of operation in the batch mode as well as continuous mode.

Fluidised bed drying in batch mode

A certain amount of wet seeds is charged into the dryer chamber where it is fluidised and interaction with hot drying air takes place and the seeds get dried. Moisture content of the seeds decreases with time and the temperature increases during drying. The whole charge is discharged after it has been dried.

Fluidised bed drying as a continuous process

The seeds are fed through the feeder into the reactor where it gets fluidised and interaction with hot inlet fluidising air takes place with consequent heat and mass transfer resulting in the drying of the seeds. The seeds are fed at one end of the dryer chamber and it goes gradually towards the discharge end in a fluidised state. The residence time of the seeds is determined by material content within the bed and the feed rate. The seeds stay inside the chamber and come out after an average (mean) residence time. The final drying condition of the seeds is determined by residence time, fluidising air temperature etc. It is a continuous system.

1st stage dryer

This is a continuous fluidised bed dryer. Moist grains are fed continuously to the dryer at one end through a screw feeder and get discharged after drying at the other end. Hot air, generated by electrical heater is fed into the dryer bottom through a distributor plate by a blower and gets exhausted to the atmosphere after use. Desired moisture content of the output grain is achieved by controlling the air temperature and the grain feed rate. Temperature of the grain must not exceed a preset value. The specifications of the laboratory pilot unit are given below.

Drying capacity:	20 kg/hr
Moisture content drop:	From initial 20-30 %
	To final 18 %
Fluidising velocity:	Up to 2 m/s
Bed area:	(1000 x 100) mm^2
Distributor Plate:	No. of holes = 570; Hole dia. = 3 mm
Air flow:	Max. 1080 m^3/h
Power requirement	
Blower:	3.73 kW
Heater:	15 kW

Experiments on fluidised bed drying of paddy on the pilot unit have been carried out and a good amount of data has been generated. Typical drying characteristic curves are shown in Fig. 9.

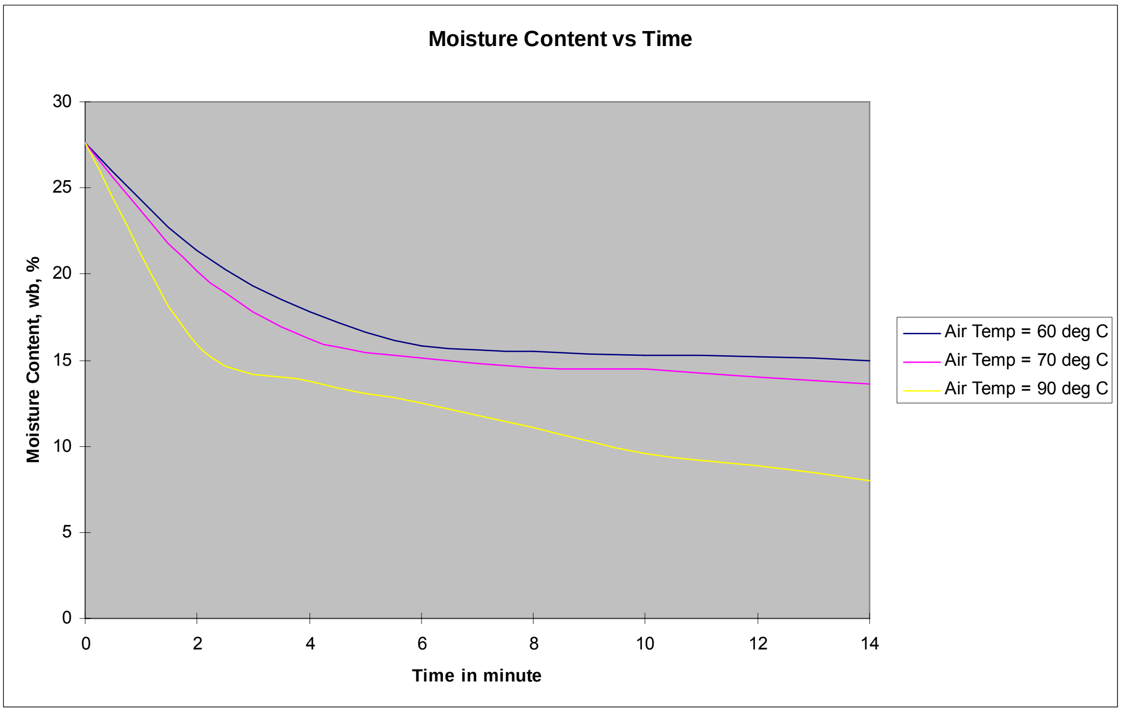


Fig 9. Drying characteristics in fluidised bed drying of paddy

In-store Drying

Unheated or natural air drying is usually performed in the grain storage bin and it is also known as ‘in-bin’ or ‘in-store’ drying.

In full-bin drying, a full bin of grain is dried as a single batch. Then the drying bin is used for storage purposes. The air flow rate provided is relatively low. Though natural air is supposed to be used, an air heating system is also kept so that supplementary heat may be supplied to the natural air during rainy seasons and during periods of high relative humidity weather. Natural air drying (without additional heat or dehumidification) can not be used if the ambient relative humidity exceeds 70 %. So also grains containing moisture higher than 20% should not be dried with natural air.

When using natural air drying, the grain is aerated (for drying) and stored in the same unit, the complete installation simply consists of a storage unit equipped with ducts for air distribution and devices for air exhaustion and a blower.

The appeal of in-bin drying is that it saves on equipment costs, by allowing the same bin to be used for drying and for storage of grain. In all cases air is passed slowly through the bin of grain, picking up moisture as it moves upwards.

2nd stage dryer

This is a storage bin for grain where a small quantity of ambient or slightly heated air (not more than 5 °C above ambient) is supplied from a blower. Hot air, generally generated by an electric heater, the ON/OFF operation of which depends upon the relative humidity of the ambient air and controlled by an automatic control system (PID), is fed into the plenum chamber of the dryer through an manifold and gets exhausted to the atmosphere after use. If the relative humidity of the ambient air exceeds a certain high value, air supply stops altogether and the blower takes start again when the humidity comes down. Grain can be stored for weeks to months together in these storage bins. The specifications of the laboratory pilot unit of in-store dryer are given below.

Bin volume:	0.962 m^3 (Φ 0.7 m x 2.5 m high)
Moisture content drop:	From initial 18-20 %
	To final 13-14 %
Airflow:	Max 20 m^3/h
Power requirement	
Blower:	1.12 kW
Heater:	2 kW

Experiments on the in-store dryer have been carried out with a good amount of data generated. Typical test data are shown in Fig. 10.

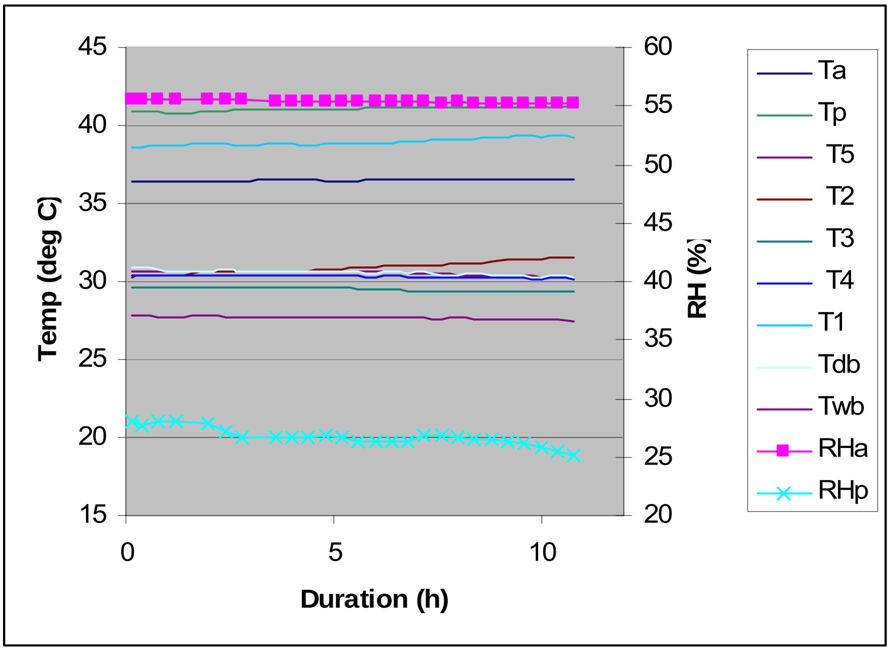


Fig. 10. Temperature and relative humidity profiles in an in-store dryer

Ta = Ambient temperature; RH_a = Ambient relative humidity; T_p = Storage bin plenum temperature; RH_p = Storage bin plenum relative humidity; T1 to T5 = Temperatures inside the bin, T1 corresponds to bottommost point and T5, the topmost; T_{db} = Dry bulb temperature of the exit air; T_{wb} = Wet bulb temperature of the exit air

7.3.4 Modelling of drying

During grain drying most of the water present in the kernels is removed by vaporisation in order to extend the microbiological and biochemical stability of the commodity. The change of phase during drying will generally be obtained by heat supplied by the drying air (convective drying). The water molecules in the grain may be bound to the ionic groups or form hydrogen bonds with each other. The energy requirement for removal of unbound water is lower than that of the bound water. The largest energy requirement is for the removal of water bound to the ionic groups.

The first drying models have been developed around 1920s (McCabe et al. 2005). Prior to drying, the grain is loaded into the dryer where the air temperature is higher than that of the wet solids. If the surface of grain is covered with a water film, it will attain the drying air temperature at the end of the heating period. The evaporation rate of water from the surface of grain will be constant as long as the surface moisture is present. This is called the constant rate period. The water movement during the constant rate period is mainly through vaporisation. Once the surface moisture has been depleted, the water from the centre of the kernel will be moving towards the surface of the kernel and the mechanism of diffusion will be determining the speed of this process. The drying rates will be decreasing with the decrease of the moisture content in the kernel. This phase of the process is called the falling rate period.

In summary, the drying process is based on the interaction of the wet grain with the drying air (Driscoll, 1995). The enthalpy is an important concept in drying since in an adiabatic, constant pressure system, enthalpy is conserved. On a psychrometric chart, the drying process can be represented using lines of constant enthalpy. The inlet air will start at a different enthalpy form the initial product. As a result, in order for the product to come to equilibrium with the air, two balances will be required, the thermal (or enthalpy) and the moisture balance. The thermal balance will generally be achieved much faster than the moisture balance. In order to understand the drying process in a single layer of grain, thin layer drying equations have been developed (Bala & Woods, 1992 and Weres & Jayas, 1994). A deep bed of grain can be represented as a number of superimposed thin layers of grain. The first layer will be a modelled as a true thin layer whereas the next layer will be affected by the outlet conditions of the first layer. The advantage of a deep bed over a thin layer is that the drying air is exposed to a larger amount of product and that more time will be needed to reach equilibrium. This results in greater moisture removal efficiency as opposed to the thin-layer where the drying air leaves the product with a significant unused moisture removal capacity.

Many deep bed dryers models have been developed in the last four decades. Cenkowski et al. 1993) reviewed the existing models and suggested three as the most appropriate to describe the process. Those were the equilibrium, the non-equilibrium and the logarithmic model. However, this list neglects the most successful model which is the so-called near-equilibrium model that is assuming thermal equilibrium without assuming moisture equilibrium. In practice, at low temperature, near-equilibrium models were found to perform better than non-equilibrium models, even for superficial air velocities such as in fluidised bed dryers (Nathakaranakule & Soponronnarit, 1993).

Drying of a single particle

A good amount of theoretical and experimental work has been / is being done to describe the drying characteristics in general and for a grain particle in particular. It was considered that moisture moves through a grain by the mechanism of diffusion. It was further postulated that other mechanisms such as capillarity, gravity, external pressure may also exist. More sophisticated models have been derived either from a classical (mechanistic) approach and /or from non-equilibrium thermodynamics. It was pointed out that for cellular materials the drying mechanism is far more complicated, since the structures are heterogeneous and the body shrinks with loss of water. The analysis /modelling on the subject need to consider changes with drying. The phenomenon has been broadly analysed by Luikov and many others. Moisture movement through the porous materials is caused by moisture gradient as well as by temperature gradient. Thus the phenomenon occurs by simultaneous heat and mass transfer in a coupled manner. The computations have been done so far mostly by different approaches: using moisture diffusion equation alone without considering thermal diffusion, using both thermal and moisture diffusion but without considering coupling effect, using boundary conditions in different manners, arbitrarily chosen heat and mass transfer coefficients. It is necessary to deal with the coupled thermal and moisture diffusion equations with appropriate boundary conditions and empirical exchange coefficients to analyse the drying process. A few attempts were made in this direction and predicted results agreed with the experiments satisfactorily. Finite difference technique has been used in some cases. Yet finite element method suits best for analysing drying of grains and materials because it can conveniently accommodate the geometries of grain particles.

In the present study, a simulation model is being developed for drying of a single grain based on the thermal and moisture diffusion equations. Finite element technique (FEM) is used for the computation which predicts moisture and temperature fields within the grain particle in a convective environment. FEM is a method of integrating weighted residuals over defined finite elements to find approximate numerical solutions of differential equations, and is used for solution of boundary value problems. In the FEM method, the element equations are developed from the equations using different methods. Galerkin's method has been applied in this case. This is still being developed to take care of more realistic physical situation and achieve precise results.

The fundamental governing equations considered are;
Mass diffusion equation:

$$\partial M/\partial t = D_m \nabla^2 M$$

Thermal diffusion equation:

$$\rho c\, \partial T/\partial t = k\nabla^2 T$$

Where:

M = Moisture content
T = Temperature
D_m = Mass diffusion coefficient
k = Thermal conductivity
ρ = Density
c = Heat capacity

The advantages of FEM are as follows:

- Greater resolution
- Greater accuracy
- Better modelling of complex shapes

Fluidised bed drying

Besides drying of a single grain particle, the drying process in a system also needs to be analysed to understand and predict the drying behaviour in a dryer. Since fluidised bed dryer is one major component in the system, the process of drying in fluidised bed has been analysed. The methodology is based on two phase theory of fluidisation in a fluidised bed. The gas phases in emulsion and bubble and the particle phase have been considered. Moisture and thermal exchanges in the processes are analysed. Mass and thermal energy balance and exchanges in the emulsion phase, bubble phase and particulate phase have been considered. Necessary equations have been developed on the basis of original conservation equations. This predicts results on variation of moisture content and temperature with time in batch process and also the behaviour in the continuous process. The results obtained so far are satisfactory in general. The model has been incorporated into the existing computer simulation 'FLUIDRY' that also makes provision for the calculation of the drying cost. Further development and fine tuning on this are still being done to achieve more realistic and precise results. The analysis is envisaged to use finally the model of single particle drying to complement the data on drying rates required. The work is in progress.

In-store drying

The in-store drying process has been modelled incorporating the effects of weather conditions. The history on variation of moisture content and temperature of grains can be predicted. This work helps programming control systems which can control the operation of the drying system to attain the desired moisture content of grains /seeds for maintaining quality and also for storage. The models are incorporated into the existing computer simulation 'INSTORE'. The computer simulation enables the user to calculate the cost of drying. This work complements that already done during the previous work in S-E and E Asia.

Germination models for seeds dried in fluidised bed and spouted bed dryers

A number of drying experiments have been conducted in the fluidized bed dryer (FBD) and spouted bed dryer (SBD) at the temperature 40-80°C by using corn, rice and wheat seeds with an initial moisture content of 20-25%. The seed samples collected during drying in each time step were subjected to standard germination test. The results of standard germination test were fitted into germination models by least square method. These models explained germination percentage changes of seeds as a function of drying air temperature, moisture content of seeds and drying time. As a result, the germination percentage changes of seeds during drying process could be well predicted by the modified Giner's model 1&2 for FBD and the modified Giner's model 2&3 for SBD. While the root mean square (RMS) of the deviations between predicted germination percentages and the measured germination percentages ($G_{predicted}$ - $G_{measured}$) from the best-fitted models were 7.9, 4.2 and 3.4% for corn, rice and wheat in FBD and 5.5, and 6.1% for rice and wheat in SBD respectively (Jittanit, 2007).

7.4 Prototype design and testing

Full-scale prototypes for both the 1st stage fluidised bed dryer and the 2nd stage in-store dryer have been installed and commissioned at Burdwan seed farm of Govt. of West Bengal. Trial runs of the two stage drying system have been done. Experiments with freshly harvested grains were to be carried out for fine tuning the operation of the system during at least two harvesting seasons. The specification of the prototype units are given below:

7.4.1 Industrial-scale two stage drying system

1st stage fluidised bed dryer

Drying capacity:	150 kg/hr
Moisture content drop:	From initial 20-30%
	To final 18 %
Fluidising velocity:	Up to 1.8 m/s
Bed area:	(2.0 x 0.25=0.5) m^2
Distributor Plate:	No. of holes = 2830; Hole dia. = 3 mm
Air flow:	Max. 61 m^3/min
Energy requirement	
Blower:	7.48 kW
LPG Burner:	2.5 – 3 kg/h

2nd stage in-store dryers

Bin volume:	2 nos.; (Φ1.6 m x 2.3 m=4.62 m^3) each
Moisture content drop:	From initial 18-20%
	To final 13-14%
Distributor Plate:	No. of holes = 11375; Hole dia. = 3 mm
Air flow:	Max 2.2 m^3/min
Power requirement	
Blower:	1.12 kW
Heater:	2 kW

The drawings of the two-stage drying system are shown in Figures 11-13.

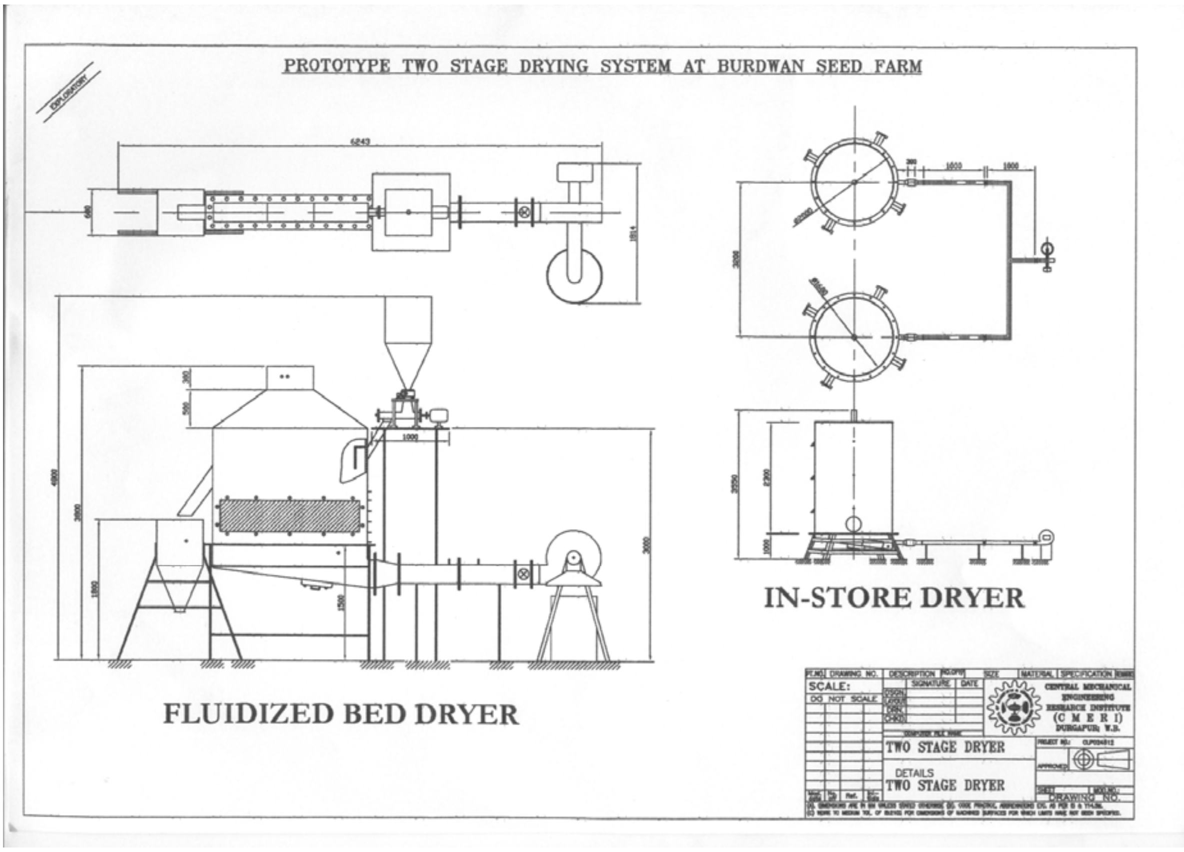


Figure 11. Schematic of the two-stage drying system

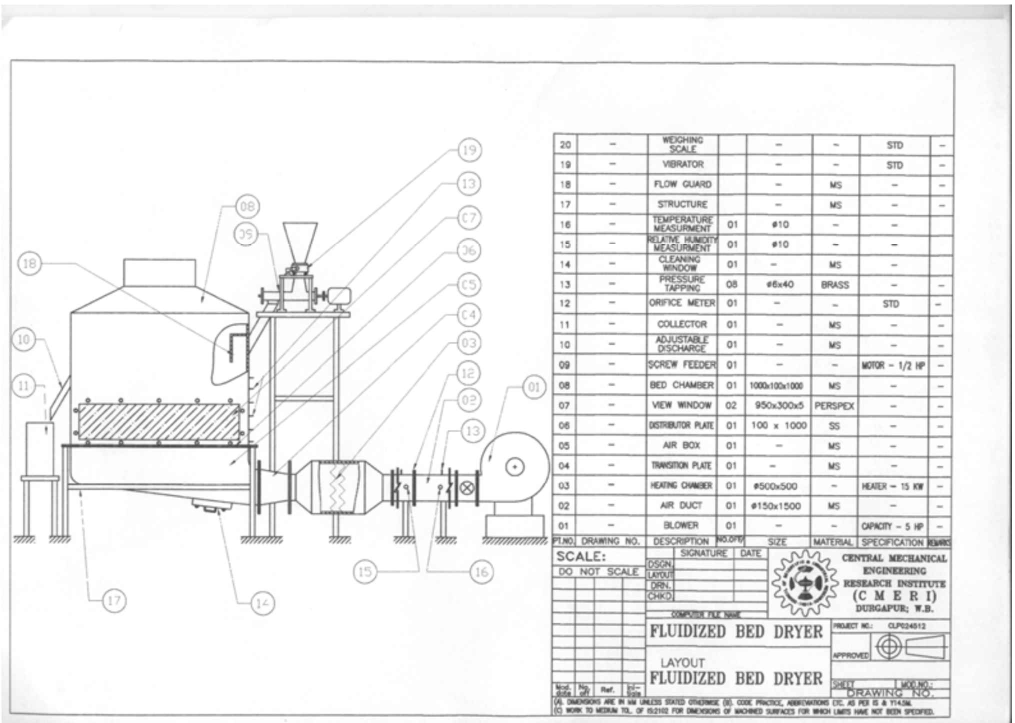


Figure 12. First drying stage: fluidised-bed dryer

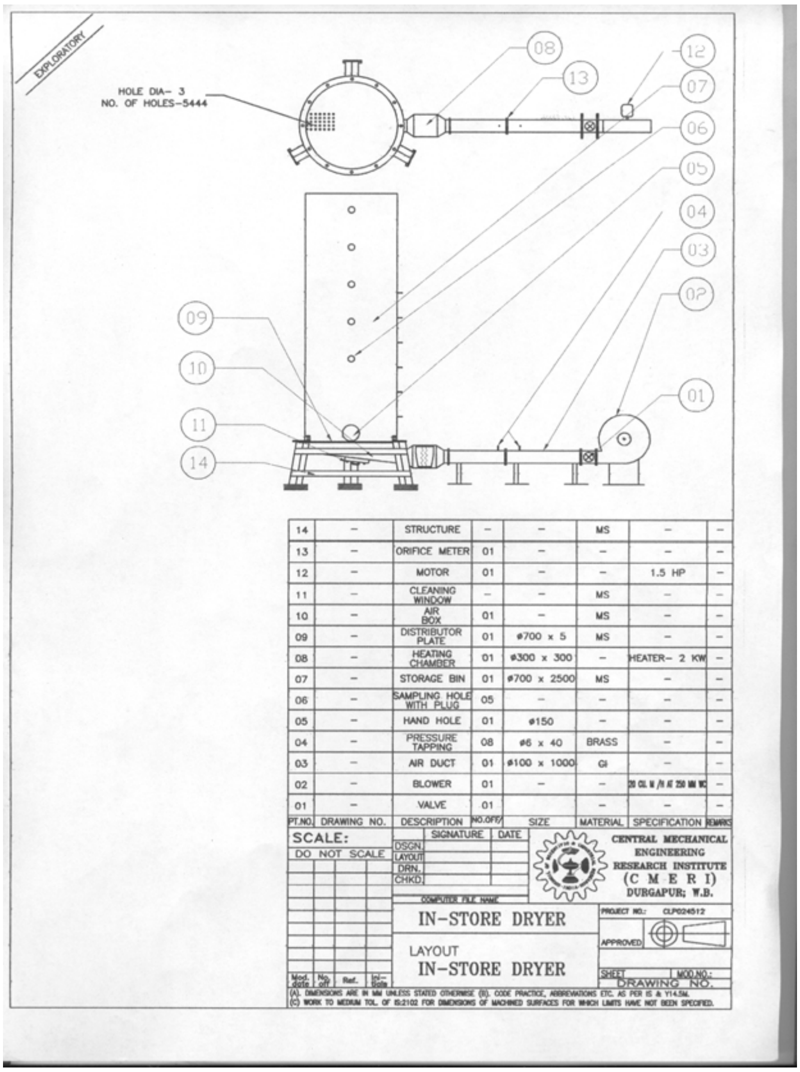


Figure 13. Second drying stage: in-store dryer

7.4.2 Interaction with users

Collaboration has been established with department of Agriculture, Govt. of West Bengal for implementation at the seed farms at district level. Burdwan district seed farm has been chosen initially as it is nearby and also is in need of a suitable drying system. Burdwan district, being called the granary of West Bengal, produces a lion's share of the total cereal crop production in West Bengal. The prototype has been set up there, trial testing done. Experiments on freshly harvested grain drying and storage will be done after getting necessary raw grains from the party. After thorough testing during at least two drying seasons, it is planned that such drying systems would also be set up in district seed farms at Jalpaiguri, Murshidabad and Bankura.

Once this is functioning satisfactorily, the system would be demonstrated to relevant people /industries. It is expected that this would help in collaboration for setting up units in other district farms. Besides, other seed /feed /grain industries which have shown interest would see the demonstration and functioning of the drying /storing system. They may like to have similar system for their farms.

8 Impacts

8.1 Scientific impacts – now and in 5 years

The project has contributed to the knowledge of the drying processes related to grain crops and varieties grown in NE India. Over recent times the phenomenological approach, based on heat and mass transfer and balance equations, has been widely adopted to study the drying kinetics in all types of dryers. Part of the credit for its success lies with the development of suitable mathematical techniques and computer power. In effect, the phenomenological approach is a true deterministic approach based on fundamental laws of physics. This has advantages and disadvantages; such an approach is based on a deeper understanding of the important physical principles in effect during drying, but the resulting equations are usually so difficult to solve that simplifications must be used, and approximations to the real-world situation applied, in order to render the equations tractable. Semiempirical models for both fluid bed drying and near ambient static bed drying have been adapted and tested for local conditions and a limited database of thermophysical properties of rice varieties from West Bengal has been developed to assist design studies. Regional weather data were gathered to assist modelling of control requirements for the dryers.

In addition to that the project made a contribution towards understanding of the drying phenomena at a single grain level.

Nowadays, mathematical solution techniques and computing power have reduced the degree of compromise that we need to make to the point where increasingly realistic simulations of the real world phenomena of drying are possible, and many real world effects can now be included. Some of these effects are (and here we focus on rice drying as a relevant example):

- Accurate geometries: rice grains are not cylinders or spheres.
- Complex structures: rice grains are not isotropic but have multiple layers which strongly affect the nature of drying and the structural properties of the dried material.
- Complex boundary conditions: the interaction between a product and its surrounding air is via a boundary layer which mediates equilibrium between the two phases, the actual drying rate from the surface layer being determined not by the moisture content on the surface but by the moisture concentration of this boundary layer, so that the boundary condition must be expressed in terms of humidity differences.
- Shrinkage of a product affects evaporative surface area and diffusion distance.
- Varying initial and boundary conditions affect drying, for example as ambient conditions vary during the day and affect the dryer supply air.
- Many properties change substantially during drying, for example diffusion coefficients, product density, specific heat and thermal conductivity. Glass transition effects are now known to be significant, and molecular binding of water to the substrate is now known to be more complex than previously thought.

For this reason, drying models in the past have separated drying into two completely different compartments, firstly the external problem of the dryer itself and its interaction with the product, analysed by heat and mass balances and often empirical transfer equations, and secondly the internal drying problem, studies of moisture movement within the product including the boundary layer and drying air.

It is now timely and possible to combine these two compartments, with effects such as case hardening, grain fracturing, quality modelling, product rewetting, non-isotropy, moisture conditioning etc all as potential fruitful areas for research.

In the past most formulations of the drying problem have been solved using the technique called finite differences, which replaces differential terms in the four primary drying equations with approximate forms based on Taylor Series expansions and the rule of central balancing. Recent work has started to apply finite elements. This allows greater flexibility in external geometries and a more robust solution due to the integral of errors over an element being forced to zero. Recent work at the University of New South Wales exemplifies this approach, and is described below for rice grain drying.

Application to drying within a single grain by FEM

Rice grains consist of multiple layers, the hull, bran and endosperm being the three primary divisions. Finite Element Methods were used to study moisture movement within a non-isotropic grain subjected to varying drying conditions.

Previous efforts to model moisture diffusion tended to use finite difference methods, based on assumed geometries such as spheres and cylinders. More recently, several authors have used finite element methods to more accurately visualise heat and mass movement within a grain, often from the perspective of analysis of fissuring. FEM is well-suited to complex geometries, non-isotropic behaviour, allows larger time integration steps, time-dependent boundary conditions, and the same code used for the heat and mass transfer can be adapted with little effort to allow stress and strain analysis. Potentially FEM is more accurate due to integration of the residuals derived from application of conservation and transport equations over volumes.

The formulation assumed simultaneous heat and mass diffusion and transfer, and used triangular annular axi-symmetric elements. Boundary conditions were modelled by the wet bulb mass transfer equations, which assume an equilibrium air boundary adjacent to the surface. The grain geometry was created by digitising microtomed medial sections through a rice grain, and the thickness of the husk, bran and endosperm layers estimated at 15 different radii from the same micrographs. Literature data on grain properties was assumed.

The resulting model is applicable to studies of moisture movement within a grain during drying, analysis of in-store dryers (where rewetting may occur), tempering (for example between passes through a dryer or in a holding bin after drying), in-field effects such as dewfall, high temperature dryers (for example fluidised bed dryers) where chemical changes occur, and for prediction of drying rates for new varieties based on compositional data. One of the first applications of the current model was to predict the thin layer drying rate of an Indian grain variety, which was then compared with laboratory data.

FEM is a method of integrating weighted residuals over defined finite elements to find approximate numerical solutions of differential equations, and is used for solution of boundary value problems.

The application of FEM in the modelling of grain drying enhances the accuracy of the predictions and is increasingly popular among scientists involved in modelling the processes related to unit operations. Given the mathematical background of the CMERI scientists who have been exposed to this technique, it can be expected that in the coming five years there will be a number of simulation models developed that will facilitate the design of drying equipment and its operation.

A further scientific impact of the project is expected to come from the development of the germination models as related to drying conditions. These models included the concept of two stage drying and the use of fluidisation as a first stage of drying. The models define the limits of use of the upper range of drying temperature leading to acceptable germination. The main advantage of the use of this modelling technique is the possible innovation in the very conventional drying methods for grain. It is expected that seed scientist will adopt the principle of using mathematical models in their research on seed drying in the next five years.

8.2 Capacity impacts – now and in 5 years

The project contributed to enhance the knowledge of the CMERI team with regard to design of drying systems. Special emphasis was placed on studies of systems including a fluidised bed as a first stage dryer and a fixed bed dryer operating under near-ambient conditions. This knowledge base includes control strategies and design of controllers for both types of dryer, and modelling systems useful in design of the dryers. On a broader scale, potential users and other interested parties from the local region, including government officials involved with receival, handling and storage of grain, now have greater awareness of the scope of dryers in various segments of the trade.

Current storage practice for seed (paddy rice, maize and other cereal grains), feed grains and paddy is in-bag in West Bengal. The project has enhanced the capability of the CMERI team to respond particularly to the need for dryer designs that give both rapid drying at harvest and quality maintenance in store, if bulk handling were introduced into the area. The in-store, second stage dryer system is appropriate for bulk paddy, including paddy seed, stored in bulk, providing effective and low cost quality maintenance even under high humidity conditions.

One local general fabricator has now developed manufacturing capability for dryers, including those arising from the project.

Additional data and design processes for grain dryers for the humid tropics, derived from the project, have been incorporated in the drying simulation ‘INSTORE’ used as a design and optimisation tool in the grain industry.

The project has been important to both collaborating research organisations in funding and maintaining research and design capability in grain drying. The collaborating institutions are two of the very few remaining public institutions worldwide with capacity in this important area.

Given the fact that both organisations are active in research and capacity building, it can be expected that the models developed under the project will be used for training of researchers and technical staff in the grain industry.

8.3 Community impacts – now and in 5 years

The project focussed on providing improvements in grain drying technology and capacity for the seed and feed industries in West Bengal and other northeastern states. The current drying system for paddy seed, and paddy, in the area is sun drying to the receival standard of <17% mc wb, followed by in-bag drying to a safe moisture content, typically <12% mc for seed. Most paddy is parboiled for local consumption, requiring re-drying after treatment. At present this is carried out by sun drying and/or drying in an LSU dryer, followed by conditioning in bag. The feed industry at present receives sun-dried maize from the producer. In West Bengal and elsewhere in Northeastern India, the sun drying after harvest is carried out by the smallholder farmers, who may produce 0.5 tonnes of grain or less for each harvest.

The two stage drying system developed by the project is currently ahead of its time. However, its development and introduction to seed farms provide an indication for the grain industry of the direction to follow. There are a number of similarities between the situation in countries of S-E Asia before adoption of bulk handling of grain and the current situation in India.

8.3.1 Economic impacts

The present harvest, drying and storage system typically meets current quality standards for both the seed and feed industries, though aflatoxin contamination continues to be a concern in the latter sector. It is difficult to speculate whether the introduction of bulk handling in the region for the major cereal crops, principally rice, will take place over the next 5 years. This is a major constraint to the uptake of the drying designs developed under this project. These designs are best suited to bulk handling, though they may be used with ‘cut-and-run’ followed by re-bagging. Introduction of bulk handling would require major changes to the current system with capital investment and social change.

A physical output from the project is the two stage pilot plant dryer installed at the Burdwan Government Seed Farm. This farm produces paddy rice seed for local distribution through Government channels. This dryer system is still undergoing technical performance testing and economic data are being gathered. It requires data from several drying seasons to carry out a reliable economic evaluation of the system.

However, the project is being implemented through government and private seed producers, farmers’ cooperatives etc. There are about 2800 rural level and 500 market level cooperative storage facilities in West Bengal with a total capacity of around 0.5 million tonnes. The National Cooperative Development Corporation (NCDC) provides cooperative storage facilities to the producers at cheaper rates. Central Warehousing Corporation and State Warehousing Corporation have a number of warehouses in West Bengal with a total capacity of about 800,000 tonnes. Through further demonstrations and training workshops it is possible that some of them decide to adopt bulk handling, at least for some of their storages.

The dryer designs may also be appropriate elsewhere in India. Increased agricultural production is a major component of current national plans to sustain current rate of increase in GDP. The latter, of the order of 8% p.a., is likely to attract more farmers towards industrial jobs and thus create suitable conditions for the adoption of bulk handling as it was the case in S-E Asia. The scarcity of agricultural land and need of improved road network in this growing economy will put pressure on the shift from sun drying towards mechanical drying.

The project team considers that the mechanical dryer system, such as the two stage system developed under this project, produces grain of superior quality to the sun drying process. Quality parameters include better retention of germination and vigour and less risk of postharvest aflatoxin contamination. Furthermore, a rapid drying system is a potential risk management tool, independent of weather. Unseasonal rain events at harvest can be economically disastrous to an individual smallholder if his/her freshly harvested grain becomes rain-affected and loses sufficient quality for it not to be accepted by the grain buyers (e.g. seed company, feed mill).

The climatic changes in the recent years increase the potential benefits that a mechanical drying system would bring to Northeastern India. This context includes the current system of handling grain in bag. The mechanical drying would reduce the risk due to unexpected wet weather in the areas within the region that are major producers of seed and/or feed.

8.3.2 Social impacts

There are several feasible scenarios for uptake of the technology in India outside the West Bengal region. The two stage dryer technology developed under this project is similar to that in successful commercial production and use in Thailand. The Thai system was developed with ACIAR support (PHT1994/037). Use of the technology can be expected where there is large scale grain production with bulk handling and storage coupled with high moisture harvesting or risk of weather damage. A possible local scenario would be the setting up of dryers as a service to smallholders who need or wish to avoid the cost/labour of sun drying. This would involve a substantial shift in the philosophy and organisation of the grain handling chain from its current form.

8.3.3 Environmental impacts

In environmental terms, introduction of a two stage mechanical dryer system to replace current drying process would be replacement of a system reliant on sun drying and hand labour with one requiring electrical power and heat energy (for the first drying stage). However, the electrical power, needed for both drying stages, is a clean energy as is generated to a large extent by hydroelectric power plants in the Himalayan region (Sikkim and Bhutan) and than supplied to West Bengal or northeastern states. As for heat energy, recirculation of exit air is a good way of reducing the energy consumption and has been included in the drying simulation package. Biomass furnaces fitted with cyclo-fans leading to very efficient combustion have been implemented in Thailand for fluidised and spouted bed dryers for paddy as a spin-off of the previous ACIAR grain drying project. Recent improvements in capturing solar energy, especially the evacuated vacuum tubes, open a new perspective for providing heat for first stage drying at high temperature. This technique is revolutionising the design of solar collectors for domestic and industrial use in China. The CMERI engineers are qualified to harness this technology and put it to use in thermal processes such as grain drying. Moreover, in-store drying is among the most energy efficient conventional techniques as specific energy consumption is second to that used by heat pump dryers.

8.4 Communication and dissemination activities

Training and dissemination formed an important part of the project. Dissemination and exchange of information were achieved through seminars, workshops, conferences and publications.

Following events were conducted during the project implementation:

1. Seminar on Grain Drying in South Asia, GDSA 2003, organised at CMERI, Durgapur, 1–2 December, 2003
2. Workshop /demonstration on drying organised by CMERI at CMERI, Durgapur on 17th January, 2005
3. Workshop on drying organised by CMERI at Kolkata on 12th December, 2005.
4. Asia Pacific Drying Conference 2005 (ADC2005) organised by CMERI at Kolkata, 13 – 15 December 2005
5. Seminar cum demonstration of two-stage drying system at Burdwan Seed Farm, 25 September 2006

9 Conclusions and recommendations

The project has resulted in following outputs:

1. Surveys on grain production, seed production and quality and infrastructure of the grain industry in West Bengal and northeastern Indian states have been conducted.
2. Industrial linkages with the seed and feed producing companies have been established.
3. Thermophysical properties of the main paddy varieties grown in West Bengal have been determined.
4. Weather data of the main grain growing areas in West Bengal (Gangetic and Sub-Himalayan West Bengal) have been collected. This includes historical data as well as recording of weather data in key locations during and beyond the life time of the project.
5. Laboratory-scale prototypes of fluidised bed and in-store dryer have been designed, built and tested. A system evaluation has been carried out.
6. The thermophysical and weather data obtained as above have been incorporated in the existing drying simulation models and the latter tested.
7. Single kernel drying model has been developed using FEM technique.
8. Germination models for spouted bed and fluidised bed dryers have been developed and validated for paddy, wheat and maize.
9. Industrial-scale prototypes of a two stage drying system comprising a fluidised bed and an in-store dryer have been designed, erected and tested at the Seed Farm in Burdwan.
10. Training workshops, demonstrations and seminars have been conducted involving manufacturers and users of drying equipment.

9.1 Conclusions

The project has produced the outputs in terms of characterisation of grain crops and weather conditions in the region of activity. These parameters were included in computer models enabling design of equipment and simulation of drying operations. The prototypes of two stage dryers have been built at laboratory scale at CMERI in Durgapur and at a commercial scale at the Burdwan government seed farm. The latter system is in place and includes fans, heaters, controllers and structures that can operate individually or as a complete integrated unit at design capacity with freshly harvested, high moisture seed rice being processed by the system, with an assessment of seed quality after drying. For a complete evaluation of the capabilities of the design and underlying principles, it will need to be run routinely over several harvesting seasons. As a matter of fact, in the Burdwan area, there are three paddy harvests per year with very different harvest characteristics. Measurement of critical performance factors continues to be carried out, benchmarked against existing practice and costs. These include seed quality, measurement of throughput to safe storage moisture content and energy consumption. These will need to be carried out to prevailing industrial standards. Without such information it will be difficult to market the system in the local region or elsewhere in India.

Once the system has been fully evaluated for paddy, the extension of the two stage drying concept to other grains, especially maize, will be attempted. Given the rapid economic development of the country it can be expected that the mechanisation of the drying operations in the country will accelerate within a 5-10 year time frame. The potential industrial users need to be firmly identified. They are likely to be outside the West Bengal area. Either of the stages may be appropriate on their own. For instance, in-bin drying alone in pulse producing areas, possibly coupled with bulk handling, may be useful, allowing both harvesting at higher moisture contents than at present and giving improved grain quality. If the process is to be introduced into other regions, it will need to be supported by appropriate modelling of grain qualities relevant to the grain and its end use with benchmarking against existing practices. Extension of the process to other grains will probably require additional research work on thermophysical properties and effects of drying regimes on quality attributes to reflect new beneficiaries.

It seems that the adoption of the two stage drying system for paddy in West Bengal in the near future may be rather slow because of current grain production and handling systems. However, the potential involvement of National Cooperative Development Corporation (NCDC), Central Warehousing Corporation and State Warehousing Corporation into system evaluation and demonstration process could provide a good promotional platform. This may attract adopters from other sectors (feed and food processors). By involving these sectors, the current goal to benefit smallholders in Northeast India through improvements in grain quality could be achieved more rapidly since the smallholders could focus on field operations whereas the processors would take care of postharvest operations. As previous experience in SE Asia and China shows, the latter benefit significantly from the economies of scale taking place when the capacity of processing equipment increases.

9.2 Recommendations

Since the project research teams have incorporated the thermophysical properties of the main varieties of paddy and weather data from the region into the existing models, the latter can be considered sufficient for design and operation of drying systems for paddy. However, further work should be done on the effects of drying on quality attributes of rice (e.g. colour, breakage, pasting properties). Furthermore, the development of FEM should be continued as, due to time constraints, this work has only been done at a very basic level. Both teams have expertise to continue developing this methodology.

Further activities have been suggested to in connection with the research and adoption of the two stage drying concept in India. These included:

- Extension of the process to other grains (e.g. wheat, pulses)
- Further modelling work and simulation of grain drying including quality attributes of rice and other grains
- Further work on reduction of energy consumption in drying, including renewable energies
- Conversion of the training module into local languages and delivery of training to various target groups
- Further interaction with local manufacturers

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11 Appendixes

11.1 Appendix 1 Photographs

Fig.A1. Laboratory-scale fluidised bed dryer at CMERI drying laboratory. 2nd from left Dr Datta, the Indian project leader

Fig. A2. Inspection of the laboratory-scale in-store dryer at CMERI drying laboratory. Mr B. Choudhury, 1st from left, Dr G.P. Sinha (CMERI Director), 3rd from left, Dr Datta 4th from left and the CMERI research team.