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Scientific perspectives on sustainable preservation of cereals in traditional silos

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Abstract

India's villages depend heavily on agriculture, with most rural households relying on the cultivation of essential grains such as rice, wheat and maize for their livelihood and food security. Although government initiatives and the Food Corporation of India have helped increase crop production to meet the needs of the growing population, the country still struggles with major post-harvest storage challenges. Traditional mud silos, or Kothis, are widely used because they are inexpensive, easy to construct and based on locally available materials, but they often fail to protect grains effectively over long periods. Issues such as moisture buildup, fungal growth, insect infestation and gradual structural deterioration lead to considerable grain losses, especially for small and marginal farmers who depend on stored produce to sustain their families and income. This review highlights the need to address these shortcomings and promote improved, sustainable storage solutions that leverage indigenous technical knowledge (ITK). By adopting eco-friendly fabrication practices, refining indigenous storage methods and using natural, locally sourced materials, farmers can achieve better preservation outcomes without relying on costly synthetic silos or chemical treatments that may pose environmental and health risks. Encouraging such sustainable, community-based approaches can help ensure safe, long-term grain storage, strengthen rural livelihoods, support national food security and maintain ecological balance in nature.

Keywords: cereals; grain silo; health and environment; indigenous practices; preservation; storage

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1. Introduction

In the earliest periods of human civilisation, communities primarily sustained themselves by hunting animals for food. Over time, as environmental challenges and unpredictable weather conditions emerged, people began seeking more reliable and consistent sources of nourishment (1). Root vegetables gradually became a staple alternative during such adverse periods. Anthropological evidence suggests that approximately 10000 years ago, early hunter-gatherer societies initiated the transition to settled agricultural practices (2). The cultivation of grains became established around 6000 years ago, followed by the development of grain storage methods roughly 4500 years ago (3).

The primary motivation for developing grain storage systems was to support the transition from a nomadic lifestyle to a more settled and semi-permanent way of living (4). Reliable food reserves enabled early communities to remain in one place for longer periods without constantly moving in search of resources (5). As these societies advanced culturally and technologically, they learned to plough land and began depending more heavily on systematic crop cultivation. The adage "necessity is the mother of invention" characterises this developmental phase (6). Communities recognised the significance of storing surplus grains to protect themselves during times of scarcity or unforeseen crises.

Significant archaeological discoveries support these early developments. For example, excavations at Tel Tsaf, a protohistoric site in the Jordan Valley dated to around 5200–4600 BC, have uncovered clay-based grain silos built within household areas (7). These structures are considered the earliest known examples of purpose-built grain storage systems. Similarly, archaeological findings from various sites in India have revealed a wide range of

ancient storage methods, including clay bins, underground pits, storage jars, raised platforms and granaries (8).

Ethnographic studies indicate that above-ground storage methods are still widely used across many regions of India (9). Farmers typically rely on bamboo baskets, tin containers, clay jars and mud bins because they are practical, affordable and easy to handle. However, in certain areas—particularly villages in Odisha—large underground silos are used to store large quantities of grain during the dry season (10). With advancements in material technology, modern storage containers made from metals and ceramics have also become common. Although these options offer improved durability, they often require the use of chemical pesticides to protect the stored grains, raising concerns about potential health risks due to contamination (11).

India has developed several small-scale storage innovations over the years, including well-known solutions such as the Pusa bin, the coal tar drum bin and the Hapur Tekka bin (12). Modern grain silos are now frequently constructed using materials like steel and aluminium (13). However, these contemporary designs are generally smaller in capacity and significantly more expensive than traditional village silos made from natural materials such as mud (14).

Traditional grain silos, commonly known as Kothis, are typically made from clay or mud mixed with agricultural residues such as rice husks and wheat husks (15). These natural fibres help strengthen the structure and improve its durability once the silo dries and hardens. Such Kothis continue to be widely used in many Indian villages today (16). Usually built in cylindrical or rectangular shapes, they allow farming households to store harvested grains safely by providing protection against pests, rodents, moisture and other environmental threats. In addition to their practical function, Kothis also carry cultural significance, symbolising abundance, stability and hope within agrarian communities (17).

A critical review of the available literature reveals a significant gap in research and initiatives aimed at preserving and improving traditional grain storage structures. In particular, there is limited work focused on enhancing their fabrication methods to increase durability and overall performance (18). This study aims to address this gap by exploring how reinforcing clay with natural fibres—such as rice husk and wheat husk—can improve the mechanical strength of Kothis. It also examines the use of indigenous bioactive materials, including neem, basil and turmeric leaf powders, which have natural pest-repellent properties and can help extend the storage life of grains (19).

The novelty of this research lies in its integrative approach: blending traditional construction knowledge with modern material innovations to create sustainable grain storage solutions that are both practical and culturally relevant. Additionally, the work provides a scientific assessment of the structural mechanics underlying these silos, including an analysis of how Kothi can reliably support the substantial weight of stored grain without collapsing, particularly at the base where stress concentrations occur.

The manuscript is organised as follows: Section 2 explains the purpose and environmental importance of adopting eco-friendly grain storage practices in rural India. Section 3 describes the fabrication process, which integrates traditional construction techniques with natural reinforcing materials. Section 4 presents a review of various indigenous grain storage systems along with their respective advantages. Section 5 provides a theoretical analysis of the structural performance and underlying physics of these silos. Finally, the concluding section summarises the key findings and offers directions for future research.

Purpose of eco-friendly grain storage in an Indian village

Grain storage is an essential component of India's grain marketing and supply chain system, helping balance the availability of food grains between years of high production and years of low production, as well as between harvest and lean seasons. Due to the wide variation in rainfall patterns across the country, agricultural yields also fluctuate significantly (20). Storage is therefore necessary not only to manage supply but also to protect grains from losses caused by rats, insects, rodents, pathogens and other biological threats. Even with existing storage practices, about 10 % of post-harvest losses remain unavoidable and nearly 6 % of the total loss is attributed specifically to inadequate storage facilities in India (21). Although storage chemicals are often used to preserve grains, they pose risks to both human health and the environment. While these chemicals may prevent spoilage, their long-term consumption can contribute to various diseases that may not be immediately noticeable (22). Before applying eco-friendly storage methods, it is important to control key factors such as temperature, moisture and oxygen levels, as these are primary contributors to grain spoilage (23). Insects and rodents continue to infest and damage stored food grains, leading to significant losses (24). Fig. 1 illustrates some of the major insect and rodent species that attack grain at different stages of storage.

Eco-friendly fabrication of grain silo (Kothi) and indigenous practices

Fabrication of grain silo (Kothi)

A traditional grain silo (Kothi) is typically made from mud mixed with post-harvest agricultural waste such as wheat husk, which helps reinforce the structure and improve its strength.

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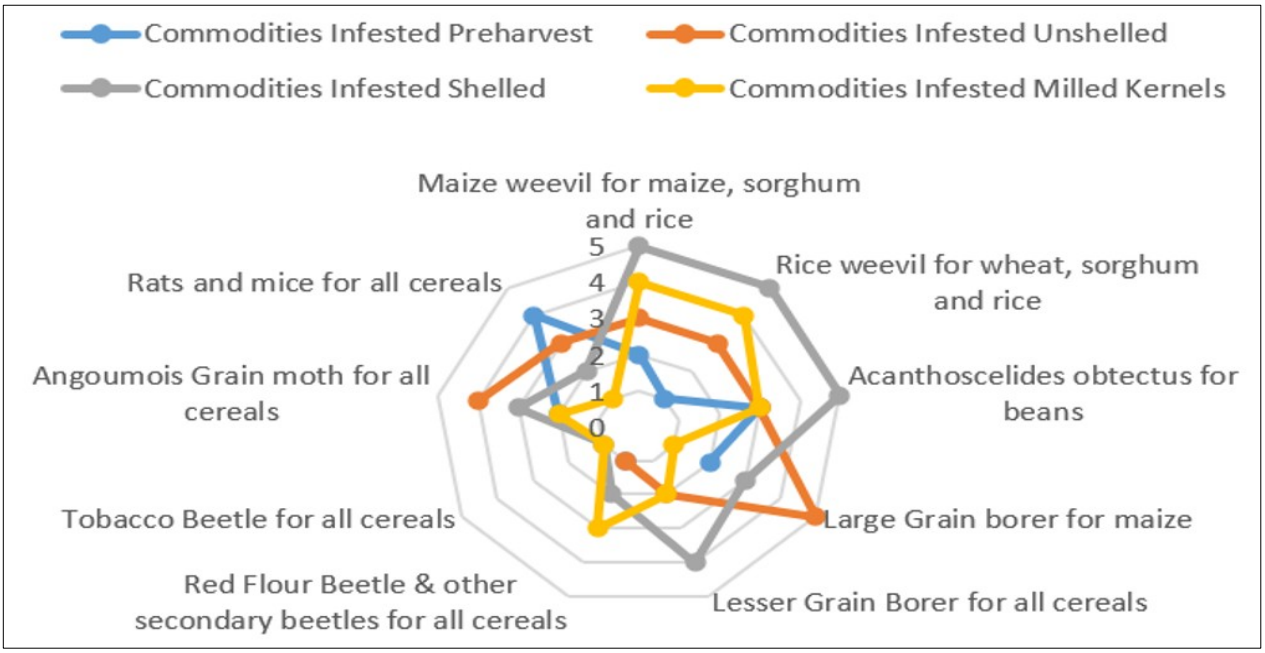


Fig. 1. Different insects and rodents destroy the food grain at different stages of grain with impact values (0-negligible, 1-very low, 2-low, 3-low to moderate, 4-moderate to high, 5-high).

However, this conventional method is not always reliable and requires refinement. In the contemporary era of rapid technological advancement (25), there is a growing opportunity to upgrade these traditional designs. An improved, eco-friendly version of the grain silo can be fabricated using mud combined with waste materials such as limestone powder, fly ash and natural fibres, such as corn husk, coconut fibres, bamboo fibres and herbal tree stalk fibres—along with neem leaf powder and a polythene sheet. Although these enhanced silos are still made by hand, some important guidelines must be followed during construction. The grains stored inside this improved structure remain safe from insects and pathogens. Fly ash and limestone powder are thoroughly mixed with water and reinforced with natural fibres and the silo is shaped using a manual hand lay-up process (26). Fig. 2 shows the fabricated model of this grain silo, which farmers often prepare in their homes. Fly ash and lime powder help the silo walls dry faster and prevent moisture absorption. A mixture containing herbal powders such as basil, neem leaf, neem seeds, grain husk and cow dung can be applied to the inner lining of the silo, acting as a natural pesticide to protect the stored grains (27). The natural fibres, including herbal stalks, serve as the structural backbone of the silo, providing strength while also reducing its overall weight. Various eco-friendly and indigenous grain storage practices are followed in our country. Some of them are briefly discussed below.

Sun-drying of grains

Sun-drying grains before storage is one of the most common and traditional preservation practices in India. In this method, the moisture content of the grains is reduced by spreading them under direct sunlight for an extended period. Nearly 93 % of Indian farmers still use this eco-friendly technique (28). Scientifically, sunlight helps destroy insects and pathogens and increases the shelf life, or latency period, of the grains. Sun-drying effectively lowers the moisture content to around 10–12 %, which is considered ideal for safe and long-term storage.

Use of ash

In this method, grains are stored in a mud pot, typically filled three-quarters with grain and one-third with cow dung or wood ash (29). The ash acts as a protective layer around the grains, as it contains silica that inhibits egg-laying, larval development and insect feeding and movement, while also helping to reduce humidity within the storage environment.

Sand application

In this method, grains are layered with sand at the bottom of the mud pot before adding the first portion of grain. As the pot is filled, additional layers of sand are placed over the grains, continuing this pattern until the pot is full. Finally, the pot's opening is tightly sealed with cow dung paste. The sand serves as both a physical barrier and an abrasive agent against insects, protecting the grains from infestation, while the cow dung seal acts as a natural repellent (30).

Plastering of the storage bin with clay and cow dung

This eco-friendly method is applied to silos made from materials such as bamboo, mud, straw mats or corn husks (31). Approximately 77 % of Indian farmers use this technique for their grain silos.

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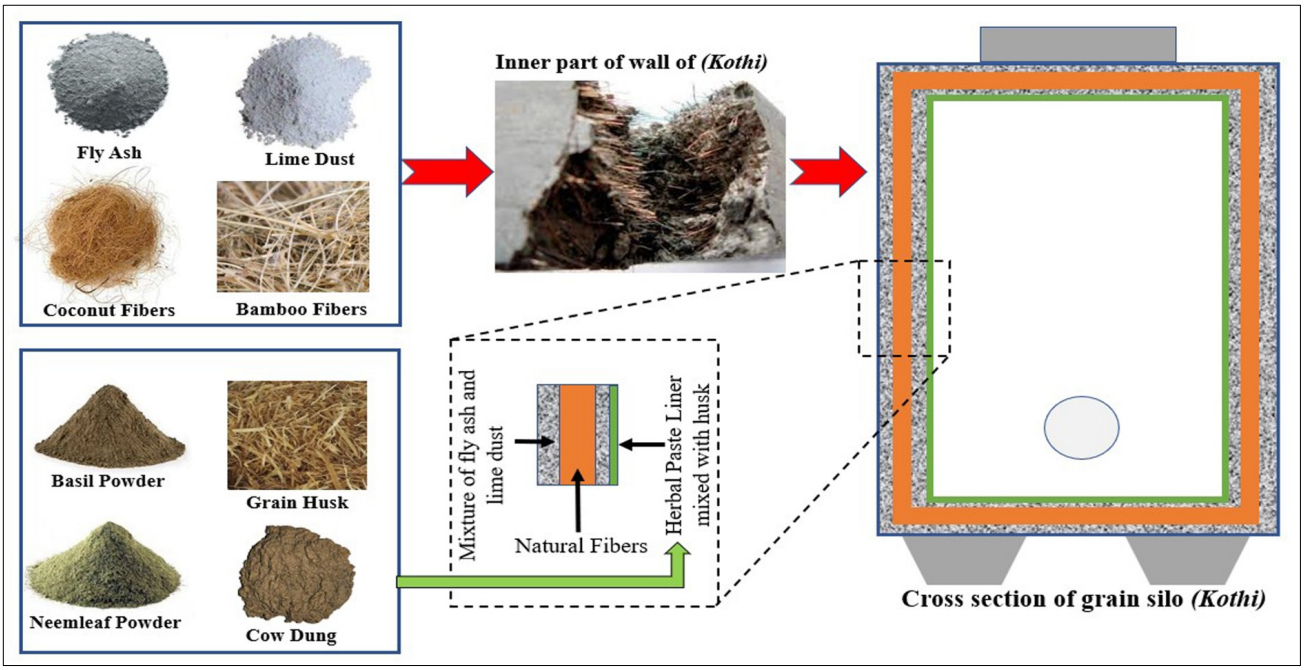


Fig. 2. Fabrication of a traditionally advanced grain silo (Kothi).

The clay absorbs residual moisture from the stored grains, while a paste made of cow dung and soil acts as a natural repellent against pests.

Turmeric application method

Turmeric powder also protects against insect and pest attacks on grains. The grains are properly mixed with turmeric powder before being placed in the silo or jute bag. The strong smell and insecticidal property of the turmeric powder save the grains up to 6–8 months (32). Turmerones and turmerone are key constituents of turmeric powder, which help preserve stored grains and make them safer for consumption. Approximately 50 % of Indian farmers use this technique.

Use of garlic lobes

Constituents like diallyl sulfide, diallyl di-sulfide and diallyl tri-sulfide are present in garlic lobes. It acts as an antifeedant, bactericide, fungicide, insecticide and repellent for storing grains (33). Garlic cloves are kept in layers at different heights in storing bins filled with grains.

Mixing of leaves

There are various herbal leaves like neem (*Azadirachta indica* A.Juss.), nirgandi (*Vitex negundo L.*) Madar used for preserving grains and seeds during the storage of grains in bins (34). These leaves are directly mixed with grains and filled in the bags and bins. These leaves act as insecticides, antifeedant, repellent and growth inhibitors of the pests. This method is widely used. This eco-friendly method is also very cheap.

Use of dried red chillies

In this indigenous method of grain storing practices, the dried chillies are kept inside the storage bin or bags. The pungency of the chillies keeps away the pests and insects from grains (35).

Matchbox application

This traditional method is frequently practiced by rural women**.** In this method, 10–15 matchboxes are kept at the bottom, middle and top of the container and tightly closed with the cap of the container. The phosphorus available on the matchstick acts as a strong repellent and helps to prevent infestation (36). Fig. 3 shows the eco-friendly grain storage practices and their contribution (%) in the Indian village.

Various traditional grain storage structures and their significance

Across India, it is observed that agriculturalists retain feed, seed and cattle feed representing 75 % of the total grain production. The remaining 25 % of the total grain production is used to sell in the market (37). There are various domestic, traditional and modern storage systems used to avoid grain quality deterioration and attack from rodents and other external factors. These domestic grain silos structures are classified according to material, economic characteristics and storage capacity (30).

1. Outdoor and indoor storage structures.
2. Metallic and cementic containers or bins.
3. Bamboo or wood-made storage structures.
4. Above ground and underground storage structures.

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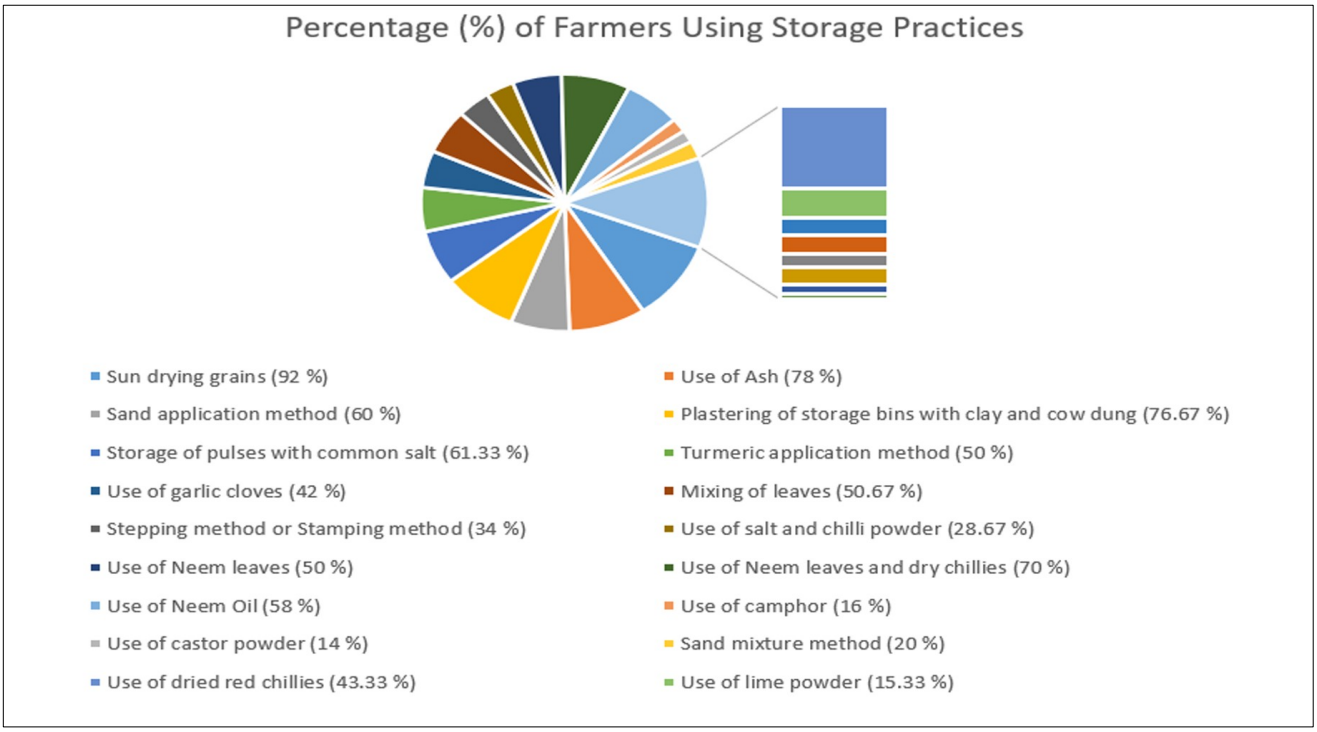


Fig. 3. Participation (%) in various eco-friendly practices for preserving food grains in India (28–40).

5. Pots, bins and storage structures are made of mud.

6. Storage structures made from the leaves of palmyra, coconut, dates, wheat and paddy straw.

Domestic grain storage structures have a low-capacity storage system. They are either indoor or outdoor type. These storage structure systems cover various structures which are generally found outdoors and indoors. The outdoor house domestic storage structures are generally named kupp, kodambae, kanaja, gummi, hagevu, etc. Whereas kothi, earthen pot, gourds pot, jute bag, mud bin, bamboo bin/basket, bharola, wooden box, steel trunk, etc., are some examples of Indoor storage structures. In India 50–70 % of the traditional storage systems are fabricated with mud, wheat or paddy straw, hay, cow dung, wood, bamboo, cement, bricks, etc. These indigenous structures are employed in rural regions on a small scale. These structures should be properly covered and made airtight so that the migration of oxygen and moisture into the grains slows down the microbial activities during storage (38, 39). The traditional grain storage structures used across India, highlighting their regional relevance, construction materials, functional advantages and supporting scientific references for sustainable cereal preservation, are listed in Table 1. Although some of these indigenous structures are discussed below.

Kanaja

Kanaja is a traditional grain storage structure, which is made up of bamboo and plastered with a mixture of soil and cow dung. It is generally made for medium storage capacity up to 2000 kg (40). Its body shape is generally round and is covered by paddy straw as shown in Fig. 4A. Grain filling in this structure at the top and after filling from the inlet opening, it is sealed by a mixture of cow dung and soil. A small hole is provided in the lid so that the grain can be extracted when needed without opening the sealed lid. There is more than one variety of grain that can be stored in this structure by providing the inner partition. Its height and diameter depend on how much storage it needs. The whole structure is at a height of about one foot from the ground so that the soil moisture of the ground does not go into the stored grain. The whole structure foundation is made of bricks, stones, wood plank, etc. The top cover is in a conical shape for avoiding the entry of rainwater into the storage structure.

Kupp

Kupp is a temporary storage structure that is made by the farmer in the farming field itself. This is made with the wooden and bamboo thin stick, which are tie-up together with jute or straw rope (41). Sometimes it is made with paddy straw tied by jute or straw rope all around, as shown in Fig. 4B. Its design is conical in shape with a circular base for better stability. It has only one opening at the top which is firmly tightened by ropes to stop the entry of rainwater, sunlight and air.

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Table 1. Traditional grain storage structures and their significance in India

Sl. No.	Storage structure	Region of predominant use	Materials used	Significance
1.	Kanja	Eastern India (Bihar, West Bengal, Odisha)	Bamboo, mud, cow dung	Elevated structure; protects from rodents; allows aeration; low-cost (40).
2.	Kupp	Punjab, Haryana, Uttar Pradesh (North India).	Straw, husk, bamboo supports, mud plaster (outer covering).	Used for bulk storage of wheat and paddy; economical and easy to construct; provides temporary protection against moisture and pests when properly covered (41).
3.	Kodambae	Southern India (Tamil Nadu, Karnataka)	Straw, bamboo, mud	Cylindrical bin; suitable for paddy storage; economical and locally fabricated (41).
4.	Kuthla (Kothi)	Northern and Central India (Punjab, Haryana, Madhya Pradesh)	Clay, mud, bricks	Large capacity; maintains low internal temperature; suitable for wheat (42).
5.	Underground pit	Arid regions (Rajasthan, Gujarat)	Soil, clay lining, ash	Airtight storage; protects against insects; risk of moisture if poorly sealed (43).
6.	Gourd pot	Tribal regions of India	Dried gourd shells	Used for seed storage; natural pest resistance; small capacity (44).
7.	Bamboo box / Basket	North-East & Eastern India	Bamboo, leaves, mud coating	Breathable; eco-friendly; can be plastered for improved sealing (45).
8.	Wooden box	Across India	Wood (e.g., neem, teak)	Durable; reusable; neem wood has insect-repellent properties (46).
9.	Steel trunk	Pan India	Galvanised steel	Airtight; protects from rodents/insects; modern adaptation (47).

Kodambae

This type of storage structure is often seen in the states of south India for storing food grains, seeds and other varieties of corn. Its wall is made with locally available materials mud, clay and cow dung mixed with soil and it is round in shape (41). The base foundation is generally made up with bricks, stones, cement etc. The foundation height is around 1 foot and the wall height is generally 3–4 feet in height.

It is covered in a conical roof, which is made with natural materials like paddy straw, palmyra leaf and bamboo sticks all are stitched together with jute thread. Sometimes whole structure is made with bricks, cement, sand and stones, where the strengthening of storage is needed (41). Its capacity is generally 1 tonne, but it can be varied as per requirement by increasing the size. For loading and unloading the grains a small door is provided on the top through which a person goes inside by using the ladder, as shown in Fig. 4C.

Kuthla (Kothi)

Kuthla is also known as kothi, it is a traditional grain storage structure that is often seen in an Indian village. It is generally made with mud, clay and hey (42). It is generally found lying in the corner of the house. People do lime painting on it so that its outer appearance looks good. Along with this, lime painting also protects against fungal attacks. There is a small circular patch in the lower part of the Kothi from which the grain is removed as per the requirement. Its shape is generally cylindrical or rectangular. The Kothi is placed at a height above the ground surface so that there is no problem with waterlogging. For this, the entire structure is placed on bricks as shown in Fig. 4D. The storage capacity of these storage structures is more than a quintal. The grain in the Kothi is filled through the opening made in the upper part and after filling the grain, it is sealed well.

Underground pit

Underground pits have been the most effective storage system for grains for a long time. They are generally found in the low-land area where the water table does not affect the storage. A pit is dug to make an underground pit, which is larger at the bottom and narrower at the top (43). The inner lining of the pit is made of clay, stones, soil and cow dung. Its opening is above the surface and is sealed with a mixture of clay and soil plate as shown in Fig. 4E. Before filling the grains in the storage pit, it must be ensured that the moisture content does not exceed 10 %. Nowadays, materials such as bricks, cement, stones and sand are used to prepare the inner lining of the pit, allowing the stored grain to remain more secure and protected. Approximately 200 kg of grain can be stored in a pit with an estimated size of 1 × 1 m².

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Gourd pot

It is a traditional method used for storing seeds and grains on a very small scale. The storage capacity depends on the size and hardness of the dried gourd shell. These gourd containers can hold approximately 5–20 kg of food grains for household use or planting purposes. Before filling the grains, the inner and outer surfaces of the gourd are thoroughly cleaned and coated with paint or varnish. After filling, the opening is securely sealed with a cork to create an airtight storage environment, as shown in Fig. 4F. It is an economical storage system in which farmers may check the condition of the grain frequently whenever they wish (44).

Bamboo box/basket

Bamboo boxes are traditional grain-storage structures made from bamboo stems and are commonly used in Indian villages to store wheat, rice, pulses and other food grains. Their size varies depending on the storage requirements. A schematic of the bamboo box is shown in Fig. 4G. Similarly, bamboo baskets are made by weaving bamboo strips together to form a container, as illustrated in Fig. 4H. In both structures, the inner surface is coated with a mixture of soil and cow dung. After filling the grains, the container is properly covered and sealed with the same mixture to create a hermetic environment that protects the grains from rodents, pests and insects. The storage life of these structures is generally 4–5 years. These traditional storage systems are known by different names across India, such as Moshti in Gujarat, Urai in the southern states and Peru in Himachal Pradesh (45).

Wooden box

The wooden box is a widely used traditional storage structure, commonly found across the northeastern states of India. It is also referred to as Peti (46). These boxes are typically made from locally available wood such as Tuni and Akharot, as shown in Fig. 4I. These types of wood possess natural resistance to wood-borer infestation, making them suitable for long-term grain storage. The storage capacity of these wooden boxes ranges from 200–1200 kg. Pegs are provided at the bottom to elevate the structure above ground level, protecting it from moisture. In many cases, internal partitions are included, allowing users to store different varieties of grains simultaneously. The wooden box is known by various names across different regions—for example, Peti in Himachal Pradesh, Kotha in Bilaspur, Bara in Shimla and Tanki in Hamirpur, among others (14).

Steel trunk

The steel trunk, also known as a metal silo, is a widely used grain storage structure made from galvanised steel sheets with a thickness of 1–2 mm. It is typically cylindrical in shape, with an approximate height of 4–5 feet and a diameter of about 1 m, as shown in Fig. 4J. The galvanised coating helps protect the structure from corrosion. The silo has a steel lid at the top for filling grain and a small outlet is provided at the bottom for controlled grain extraction as required. These structures have a storage capacity of up to 2 tonnes. Metal silos are commonly used in states such as Bihar, Uttar Pradesh, Jharkhand and Madhya Pradesh, among many others. Farmers generally store maize, wheat, rice, pulses, millets, mustard seeds and similar commodities in these steel trunks (47).

However, the comparative evaluation of traditional grain storage structures indicates that each system offers distinct advantages depending on storage requirements; however, when scientifically optimised, the modified Kothi (Kuthla) emerges as a superior alternative to even modern steel trunks (Fig. 5). Kanja demonstrates moderate performance (moisture control, pest protection, capacity, durability) and is suitable for maize and paddy due to its elevated, well-aerated design. Kodambae, with slightly lower durability and moderate efficiency, is primarily suited to short- to medium-term paddy storage because of its straw-based insulation (5). The traditional Kothi shows strong performance (moisture control, capacity) and when modified with improved sealing, lining materials or botanical protectants, it can achieve enhanced pest resistance and moisture stability comparable to hermetic systems. Underground pits provide excellent moisture control (9) and pest protection (8), particularly for millets and pulses, but require careful sealing to avoid moisture ingress. Gourd pots and bamboo baskets are more suitable for small-scale and short-term storage due to their lower capacity and protection levels, whereas wooden boxes offer good durability and natural insect resistance, especially when constructed from neem wood (8). Although steel trunks exhibit high scores in moisture control, pest protection and durability (9), their limitations include condensation risks under temperature fluctuations (48), higher cost and lack of breathability. In contrast, a modified Kothi, with its thick earthen walls providing thermal buffering, improved internal lining to reduce moisture migration and integration of traditional biopesticides (e.g., neem, ash), ensures a balanced microenvironment that minimises spoilage while maintaining grain quality. Therefore, from a sustainability, cost-effectiveness and large-scale rural applicability perspective, the modified Kothi can be considered the most suitable and scientifically robust storage option for cereals such as wheat and sorghum.

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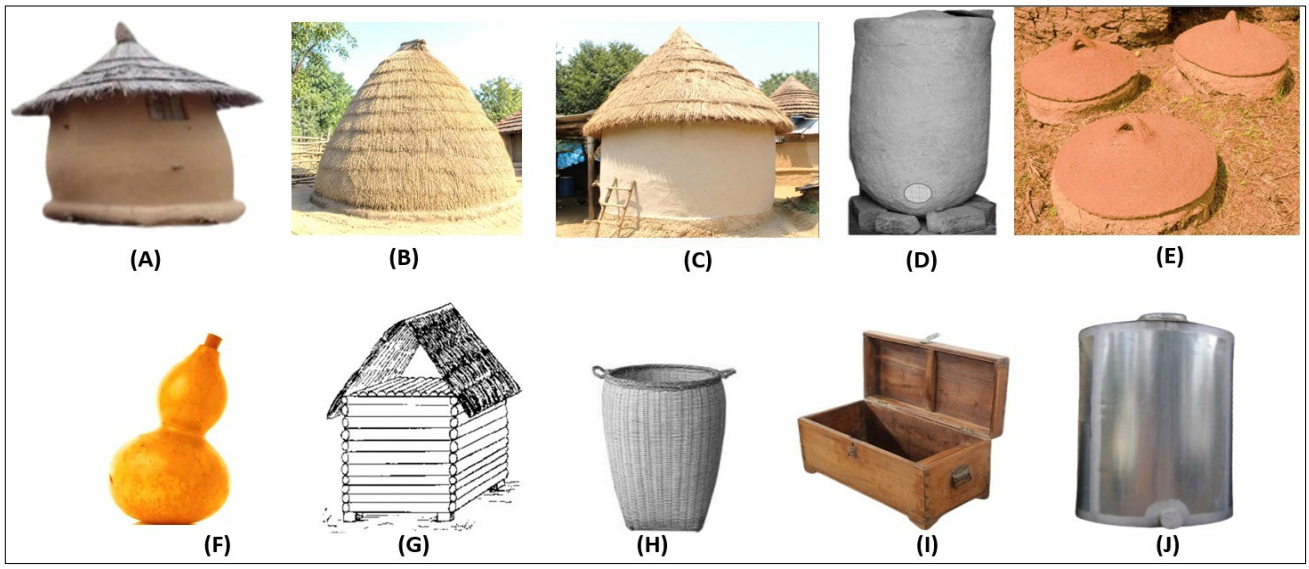


Fig. 4. Various traditional grain storage systems used in India. (A) Kanja(40); (B) Kupp (41); (C) Kodambae (41); (D) Kuthla (42) (Kothi); (E) Underground pit (43); (F) Gourd pot (44); (G) Bamboo box (45); (H) Bamboo basket (45); (I) Wooden box (46); (J) Steel trunk (47).

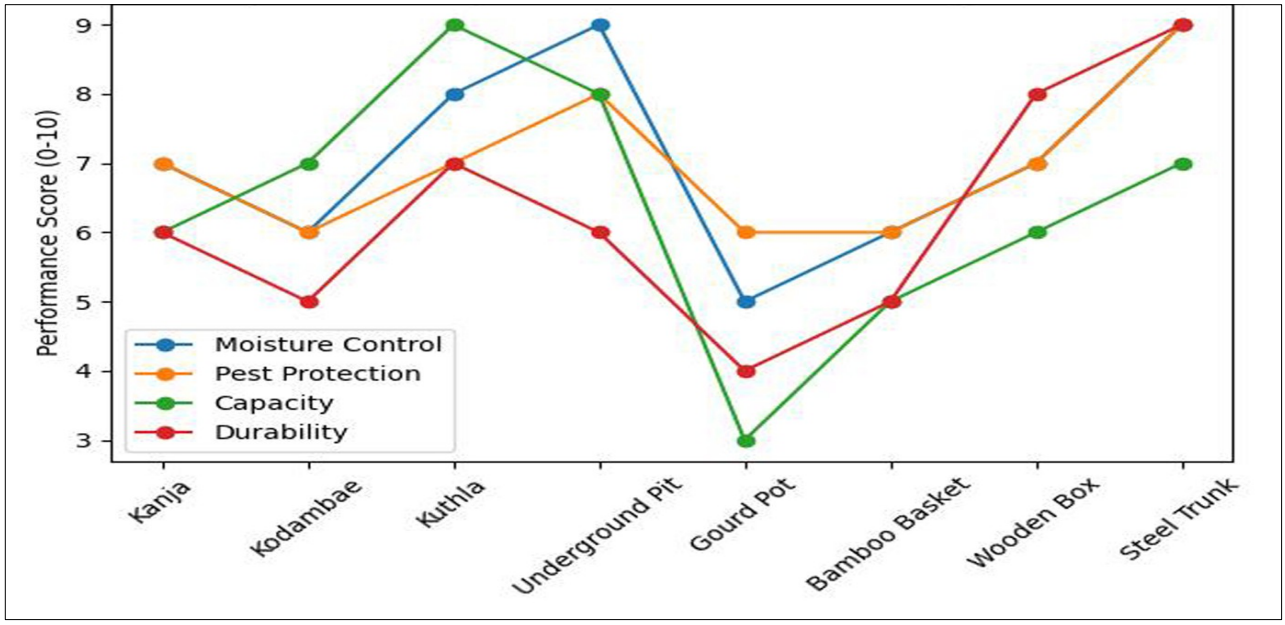


Fig. 5. Comparative performance of grain storage structures.

Significance and physics behind grain silo (Kothi)

Significance of grain silo (Kothi)

Grain silos (Kothis) are commonly observed in many Indian farming households, where traditional systems have long been used for storing cereals. Among these, mud-based grain silos (Kothi) are particularly significant due to their low cost, local availability of materials and inherent thermal insulation properties. In recent decades, however, the use of chemical pesticides and fumigants in grain storage has increased substantially. Commonly used chemicals such as malathion, aluminium phosphide and chlorpyrifos-methyl are effective against storage pests but pose serious health and environmental risks if misused or overused (49). Studies have shown that pesticide residues can persist in stored grains and enter the food chain, leading to chronic health issues including neurological disorders, respiratory problems and carcinogenic effects (50). Moreover, excessive reliance on chemical fumigation has contributed to the development of insect resistance, reducing long-term efficacy (51).

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Recent research emphasises the importance of sustainable and eco-friendly grain storage solutions, particularly in developing countries where post-harvest losses can reach 10–20 % due to improper storage conditions (52). Traditional structures such as Kothis offer natural advantages, including passive temperature regulation and reduced moisture fluctuation, which are critical factors in minimising fungal growth and insect infestation. When modified with improved sealing, internal linings and integration of botanical protectants such as neem-based products, these systems can significantly enhance storage efficiency while maintaining grain quality (53). Additionally, hermetic storage principles —such as reduced oxygen levels—have been successfully adapted into traditional systems, further improving their performance without reliance on synthetic chemicals (54–56).

The development of an advanced or modified grain silo (Kothi), as discussed in this study, aligns with these sustainable approaches by combining indigenous knowledge with scientific improvements. Such systems are not only eco-friendly and cost-effective but also farmer-centric, making them highly suitable for rural adoption. Furthermore, pre-storage indigenous practices, including sun drying, ash treatment and the use of plant-based repellents, play a crucial role in enhancing the effectiveness of these storage systems. Therefore, upgrading traditional storage technologies through scientific intervention can contribute significantly to reducing post-harvest losses and ensuring food safety, thereby supporting global efforts to meet the increasing demand for food and energy in a sustainable manner (57–59).

Structural and granular mechanics

Food grains occur in a wide variety of shapes and sizes—pulses are generally round, wheat grains are elongated and slightly thicker, while rice grains are long and slender. Various grains such as madua (finger millet), barley (Jau) and pearl millet (Bajra) can be efficiently stored in a grain silo. Grains exhibit unique dual behaviour that is of particular interest to engineers and physicists: they can behave both as a solid and as a fluid. For example, if a large opening is made at the bottom of a sack, grains exhibit fluid-like flow characteristics. At the same time, they retain solid-like properties when at rest. Grains take the shape of the container in which they are stored-forming a cylindrical profile inside a silo (Kothi) and a nearly spherical profile inside a traditional vessel (Batlohi).

Moreover, grains also exhibit solid-like behaviour because they remain densely packed and each grain itself is a solid particle. This dual nature is not limited to cereals; mustard seeds, gram beans, Jamun seeds and many other granular materials show the same characteristics. Granular materials such as seeds and cereals are ubiquitous and represent the second most handled material in industries after water. In this context, the dual physical behaviour of food grains stored in a silo (Kothi) is explained. Fig. 6 presents a model of a grain silo (Kothi), which is considered to be cylindrical in shape with a radius R, circumference $C = 2\pi R$ and cross-sectional area $A = \pi R^2$. The average mass density of the stored grains is denoted by ρ and the coefficient of friction μ along the inner wall of the silo is assumed to be constant.

Text presented in the model, where:

P: Pressure offered by the grains.

x: Distance from the top.

L: Height of the grain filled.

dP: Differential pressure between two points.

dx: It is an infinitesimal distance.

Food grains exhibit both solid-like and liquid-like behaviour. In general, the pressure exerted by a liquid is determined by the product of its density (ρ), gravitational acceleration (g) and depth (h), expressed as $P = \rho gh$. If grains behaved purely as a liquid, the pressure at the bottom of the silo would be extremely high, enough to rupture the structure. However, silos do not fail under such pressure. This is because grains also behave like a solid; they generate friction against the silo walls in an upward direction, which counteracts and significantly reduces the downward gravitational pressure of the grains. Thus, two forces act on the grain mass: a downward force due to its weight and an upward frictional force exerted by the silo walls, which stabilises the stored material and prevents structural failure.

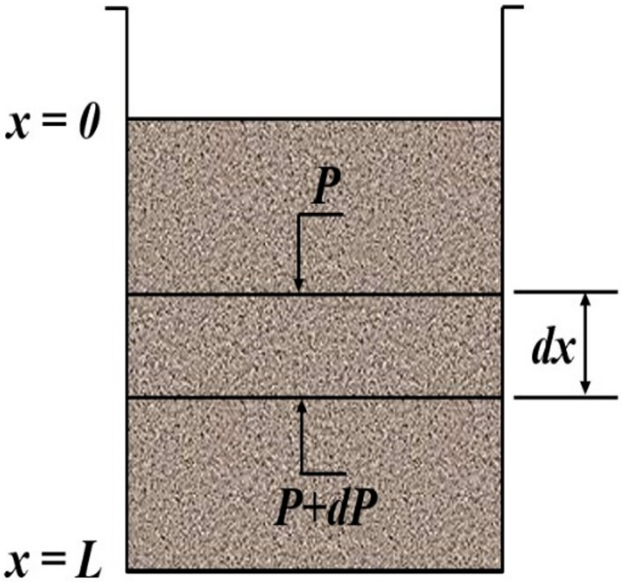


Fig. 6. Cross-section model of grain silo (Kothi) filled with grains.

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Scientific and quantitative analysis

The pressure is also defined by the perpendicular force per unit area, i.e., P = F/A and the unit is N/m2. Another well-known equation of pressure is P(x) = ρgx. Hence, the downward force exerted by the grains can be written as AP(x). There is another law of fluid mechanics called Pascal's law. It states that pressure in a fluid is distributed evenly in all directions within the fluid. Therefore, the force exerted on the wall of the grain silo for a small depth dx is P(x)Cdx, where C = 2πR is the circumference of the cylindrical grain silo mentioned above. If we make another assumption that the grain behaves like a solid, then the upward frictional force acting on it due to the normal reaction is μPCdx. The net force acting on the grain slab, dx, is written as:

$A(P+dP)-AP=A\rho gdx-\mu PCdx$ Eq. 1

or $A(P+dP-P)=(A\rho g-\mu PC)dx$

or $AdP=(A\rho g-\mu PC)dx$

$ordP/dx=\rho g-(\mu PC)/A$ Eq. 2

After rearranging, we obtain:

$$\int_{P_{atm}}^{p(x)} \frac{dP}{\rho g-\frac{\mu PC}{A}} = \int_{0}^{x} dx \;;$$

where P_{atm} is the atmospheric pressure form the top

$$-\frac{A}{\mu C}\left[\ln\left(\rho g-\frac{\mu P(x)C}{A}\right)-\ln\left(\rho g-\frac{\mu P_{atm}C}{A}\right)\right]=x$$

After applying logarithm property $\ln(x) - \ln(y) = \ln(x/y)$

Thus,

$$or \quad -\frac{A}{\mu C}\left[\ln\left(\frac{\rho g-\frac{\mu P(x)C}{A}}{\rho g-\frac{\mu P_{atm}C}{A}}\right)\right]=x$$

$$or \quad \left[\ln\left(\frac{\rho g-\frac{\mu P(x)C}{A}}{\rho g-\frac{\mu P_{atm}C}{A}}\right)\right]=-\frac{\mu Cx}{A}$$

After yields the Exponent

$$\rho g-\frac{\mu P(x)C}{A}=\left(\rho g-\frac{\mu P_{atm}C}{A}\right)e^{-\frac{\mu Cx}{A}}$$

$$or \quad \frac{\mu P(x)C}{A}=\rho g-\left(\rho g-\frac{\mu P_{atm}C}{A}\right)e^{-\frac{\mu Cx}{A}}$$ Eq. 3

$$or \quad P(x)=\frac{A}{\mu C}\left[\rho g-\left(\rho g-\frac{\mu P_{atm}C}{A}\right)e^{-\frac{\mu Cx}{A}}\right]$$ Eq. 4

Eq. 3 is the main result and it explains how a grain silo works.

This equation is also dimensionally balanced, proof shown below:

$$[P(x)]=\frac{[A]}{[C]}\left[[\rho][g]-[\rho][g]+\frac{[C]}{[A]}[P_{atm}]\right]$$

$$or \quad [P(x)]=[P_{atm}]$$

There are two cases taken,

(a) Let the grain silo be the small height x

As $x \to 0$;

$e^{-\frac{\mu Cx}{A}} \to 1$

So, $P(x) \to P_{atm}$ (As,Expected) Eq. 5

So, $P(x) \to P_{atm}$ (As,Expected)

(b) Let the grain silo be very tall, Then

As $x \to \infty$;

$$\left(\rho g-\frac{\mu P_{atm}C}{A}\right)e^{-\frac{\mu Cx}{A}} \to 0$$

$$So, \; P(x) \to \frac{A}{\mu C}[\rho g]$$

$$P(x) \to \frac{A\rho g}{\mu C}=P_0 \quad (P_0 \text{ is a constant})$$ Eq. 6

The overall explanation suggests that a very tall grain silo with a large volume of grains will not rupture itself from the bottom of the lower side. The reason is that as depth increases, the pressure does not increase proportionally but approaches a constant. It is evident that high surface roughness helps to increase the coefficient of friction μ. In Eq. 3, μ is in the denominator; hence, the constant pressure will be accomplished over a small depth of the silo. The bulk density of rice is typically 550 kg/m^3. Taking a radius of 40 cm so that the area-to-circumference ratio (A/C) is R/2, i.e., 0.20 m and assuming the coefficient of friction μ = 5. From Eq. 3, we have a value of pressure of 215 Pascals. This pressure of 1.6 mm of mercury (Hg) is very low since typical human blood pressure is 100 mm of Hg. The variation in the little pressure depends on the bulk density of the stored grains and the coefficient of friction.

2. Conclusion

Traditional grain storage structures, such as mud silos, are gradually being replaced by modern metal bins; however, these traditional (or ancestral) systems offer unique advantages in maintaining stable temperature and moisture conditions, which can enhance seed viability and reduce post-harvest losses. This study demonstrates that traditional mud grain silos can be upgraded using eco-friendly and locally available materials, combining cultural heritage with modern improvements to increase efficiency, safety and longevity.

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Adopting and improving traditional storage methods can significantly reduce the reliance on chemical preservatives, germicides and pesticides, thereby minimising their adverse effects on human health and the environment. Future work should focus on optimising the design, thermal insulation and structural durability of mud silos, integrating modern monitoring techniques and evaluating their effectiveness across different climatic conditions. Preserving and scientifically enhancing traditional storage practices can contribute to sustainable agriculture, ensure food security and conserve cultural heritage to support the health and well-being of society.

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Authors' contributions

KR and her team from MBAC provided technical guidance, innovative conceptual inputs, and critical review support throughout the study. MKN and his team carried out an extensive literature review, designed and executed field surveys across villages in Bihar and Jharkhand, collected and statistically analysed the data, and prepared the manuscript for publication. UK, MI, and PS contributed significantly through methodological refinement, data interpretation, domain-specific insights and critical revisions, thereby strengthening the analytical rigor and overall quality of the study. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest

Authors do not have any conflict of interests to declare.

Ethical issues

None

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