

Grain Silos – Holistic Approach for agricultural sustainability: A Review

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Abstract

Granular materials and its storages in silos are of interest for industries and academics. Silos are used in agricultural sector for conservation of food grains. The global population is predicted to grow from 7.7 billion to 9.7 billion by approximately 2050. The agricultural food demand is going to increase tremendously. Annually about two billion tonnes of grain products are produced. But pandemic situations, natural calamities and wars have significant effects on grain production. Huge loss of agricultural products is occurring due to poor storage. Reduction in loss is essential to preserve natural resource and improve livelihoods.

Hence re-evaluation of traditional grain storages in terms of ecosystem and sustainability is essential. Silo have become essential in addressing these challenges by ensuring long-term preservation and distribution of grains. Proper management and monitoring can protect grains from deterioration for extended periods.

Global and Indian scenarios are compared to assess advancements and opportunities. This review addresses the challenges and safety concerns. The article also examines initiative by government of India. The review might be interested to policymakers, researchers, farmers, engineers and leaders of emerging economics to make strategic decisions regarding the selection of silos. Gaps are emphasized and areas for further research are highlighted, particularly in automation. Recommendations are being made to guide future developments in this area.

Keywords: Silo, Grain, Sustainability, Innovative, Ecosystem.

1. Introduction

Globally, about two billion tonnes of grain products are produced annually, the population is exponentially growing. Agriculture is important for economy, and accounts for more than 14% of the Indian GDP. Various policies are implemented to cope up with increasing food demand. Government of India projected vision of “Viksit Bharat 2047” developing an “Atmnirbhar Bharat”. Development of silos is a commendable initiative of Indian Government. Department of Food and Public Distribution and the Food Corporation of India have developed modern grain silos, to position the country as a leader in sustainable and efficient food management [1].

The article also examines techno-commercial aspects of grain silos, providing insights into its feasibility and viability, which might help readers for strategic initiative to obtain sustainable agriculture. The review might be interested to policymakers, researchers, farmers, engineers and leaders of emerging economics to make strategic decisions regarding the selection and design of silos [2] and can assist to reduce the gap between grain production and availability. This critical area is neglected till date. Understanding the unique needs of different granular products and developing solutions tailored to specific granular materials have a pivotal role in optimizing silo usage. This review suggests different areas for research to manage the man-made ecosystems and sustainability [3].

Silo design is highly regulated. Various legal and statutory rules and regulations are to be followed, to ensure safety, environmental compliance, and operational efficiency. Designers must comply with various guidelines of building codes, safety standards and regulations, fire protection requirements, environmental protection laws. By strengthening the quality system approach, silos are becoming more appealing to farmers and various industries [4].

Preservation of food grains is critical to ensure food quality and security. Grain products are prone to deteriorate, and silos plays a crucial role to protect grains from humidity, temperature fluctuations, and pests, etc. [5]. Grain silos can help to overcome these challenges by ensuring long-term preservation and distribution. The market of silos for grain storage is foreseen as a game changer.



Figure 1: Silo: Holistic approach towards Agriculture, food security, sustainability and Ecosystem.

2. Global Demand and Concerns:

The global population is predicted to grow from 7.7 billion presents to 9.7 billion upto latest by 2050. This is going to increase demand of agricultural food tremendously. Most of the countries have intensively concentrated on use of bare land for enhancing food grain production, and extensive control on population [6]. Food demand is going to be major challenge and to overcome the various strategies and policies are under implementation. It requires innovative concepts, which might lead to good returns along with increase in grain production. Cereal grains, like maize, rice and wheat are the most popular grain products in most of

the countries. [7]. Major food losses are due to improper storage, inadequate knowledge and lack of technological development. Hence large amount of agricultural food is lost as food waste [8].

India, china, need to be more concerned for grain storages and food loss due to large amount of population. Due to demand of small grain storages, China executed the “Scientific Grain Storage Project (SGSP)” to implement advanced storage silos [9]. The well-known organisation of united nation i.e. Food and agriculture organisation guided that storage capacity of grains in country must be minimum 20% higher than actual annual production. In regions like Ukraine, these grain storage plant systems not only safeguard vital seeds but also contribute to a broader global impact. Despite challenges, such as the threat from Russia, Ukraine has strategically utilized its grain storage facilities to establish a new shipping corridor through the Black Sea [10]. This holistic approach of grain silo is not only ensures the safety of stored grains but also facilitates the export of grains, providing a lifeline to regions.

In the entire landscape of agriculture sector in global, grain storage silos provided hope to the farmers, governments and industries. Silos weave a story of resilience and global impact in this sector [11]. Innovative silos stand as a pillar to facilitate storage of grains and to ensure a smooth flow of grains across the world. These shape the narrative of the industrial and agricultural world and embodying the essence of stability and sustenance for next generations to come. The grain storage facility proves to be an economic booster. Grain silos have come out as a revolutionary innovative storage system. Silos are having various advantages which go beyond the traditional storage methods. In today’s scenario, agriculture sectors are facing the challenges of cost effective and increase in productivity. Grain silos have demonstrated to be the solution to a multitude of crucial issue. Hence, new technologies in grain silos must be flourished to encourage improvement in design of silos based on diversity. The production of grain in top countries are tabulated in table No.1 for consecutive three years. [12].

Tabel 1: Production of food grain of top countries for consecutive three years. [12]

Sr. No.	Country	Production of food grain (million tons)		
		2023-24	2024-25	2025-26 Projected
1	China	578.6	588.8	590
2	United States	458.9	451.6	500.8
3	India	305.5	324.8	330.6
4	Brazil	140.1	158.8	152.7
5	Russia	134.7	117.2	121.7
6	Argentina	76	78.6	82
7	Canada	60.9	63.5	64.1
8	Ukraine	62.8	56.9	61.4
9	Australia	40.9	51.8	54.1
10	Pakistan	48.3	49.7	48.9

11	Indonesia	45.7	47.2	46.9
12	Turkey	38.6	34.3	34.2
13	Mexico	32.7	31.1	31.9
14	Thailand	25.4	25.9	25.9
15	South Africa	16.0	19.0	19.1
16	Other states	759.2	752.9	766.1
Total		2824.3	2852.1	2930.4

3.0 Indian Scenario

In India, storage systems like bags, metal bins, etc. are used for storage of grains. The approximate capacity of storages required ranges from 0.5 to 2 tonnes. Whereas the various agrochemical processing and milling industries needs storages up to 20,000 tonnes to fulfil processing capacities. So, agrochemical processing industries are favouring for big silo structures. The bulk storage silos require less space. These silos are also accompanied with various mechanised systems for loading/unloading, fumigation and aeration of grain [13]. Along with farmers and processing units, government is also need of bulk storage silos to keep huge number of grains to ensure food sustainability and security of entire population. Commercial silos for grains by government and agrochemical processing industries are also attracts for techno commercially feasible silo system, consistency in quality, preventive action for grain loss, various policies to enhance capacity and technological development in storage. Food grain production data since independence is plotted in figure 2 (Data from Press Information Bureau) [14].

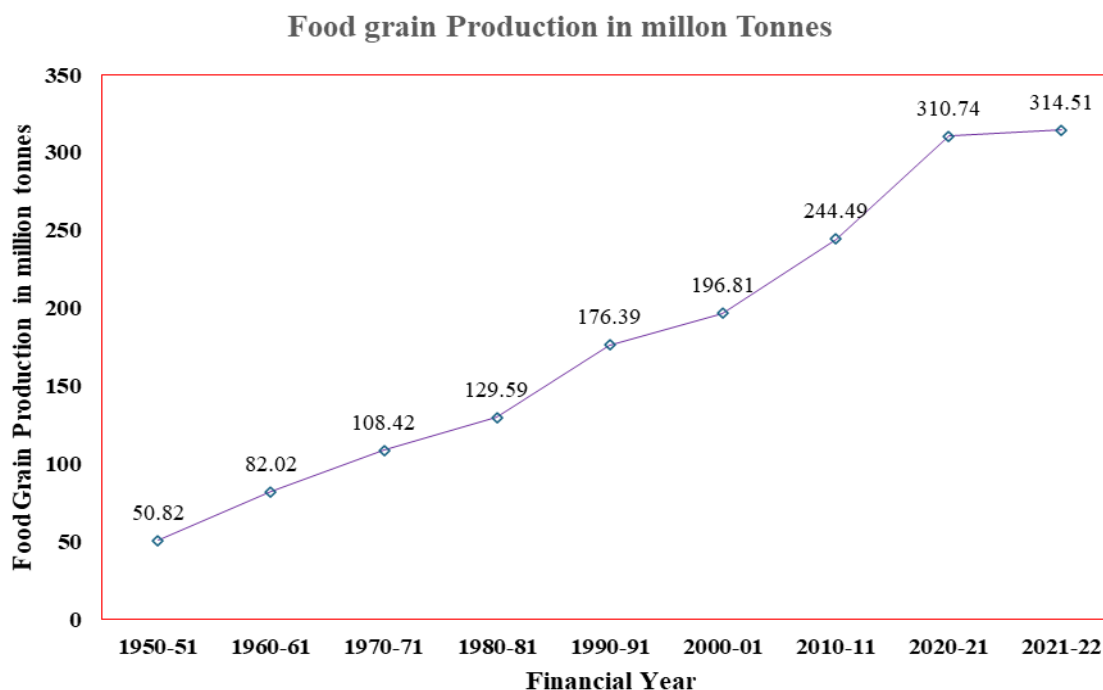


Figure 2: Food grain production Since 1950-51 to 2024-25 [14]

India has struggled a lot for the efficient and effective abundant quantity of grains. This innovates storage system have served the purpose and reduces the significant losses due to various environmental factors. In India, annual storage has been estimated at 14 million tons of grains worth going down the drain every year due to storage losses. Insects take a huge bite out of this, causing huge financial losses. As per report by World Bank, per year India faces losses of grains ranging from 12 to 16 million MT each year. Losses of 2 to 4 percent are reported due to pests. Rats contributes at around 2.5 percent, and 0.68 percent due to moisture. This is a great loss indeed. In India, usage of silos for storage of grains had accelerated momentum. This has helped to minimise losses of food products due to poor and insufficient storage facility [15].

4 Initiative by Government of India.

Department of Food and Public Distribution along with the Food Corporation of India (FCI) has taken initiative for installation of silos through partnership between public and private sector. [16]. FCI had implemented bidding procedure for silos at 249 locations for grain storage of 108 lakh MT capacity [17]. As the steel is being major component comprising approximately 30 % of overall project cost, the policy was made to promote local steel manufacturers. The Government of India had implemented “Make in India” policy for this project, and which will be carried out by partnership between public and private sectors. FCI has successfully developed various state of arts silo facilities under the model of Public-Private Partnership (PPP) [18]. FCI under Ministry of Consumer Affairs, Food and Public Distribution carried out this projects [19]. These projects initiated a significant achievement in developing effective supply chain of essential commodities, efficient storage facility and sustainable solution for modernizing India’s food grain facility [20].

FCI under this ministry has successfully launched six operational silos in collaboration with private sectors. These silos are strategically located in different locations in India. This Silo facilities mainly aimed to modernise India’s food grain storage and distribution. This revolutionary silo project found a significant step towards strengthening India’s food security ecosystem. These silos are self-possessed with successfully operational mode to enhance the capacity, efficiency and sustainability of India’s grain Management system and proven FCI as a backbone of food grain supply chain [21].

Table 2: Silo Projects by Indian Government. [20]

Sr. No.	Project	State	Done By	storage capacity	Completed On
1	Darbhanga Project	Bihar	M/s Adani Agri Logistics Ltd.	50,000 MT	April 2024
2	Samastipur Project	Bihar	M/s Adani Agri Logistics Ltd.	50,000 MT	May 2024
3	Sahnawal Project	Punjab	M/s Leap Logistics Ltd.	50,000 MT	May 2024
4	Baroda Project	Gujarat	M/s Leap Logistics Limited	50000 MT	May 2024
5	Chheheratta Project	Punjab	M/s NCML Chhehretta Pvt. Ltd.	50,000 MT	May 2024
6	Batala Project	Punjab	M/s NCML Batala Pvt. Ltd.,	50,000 MT	June 2024

These silo projects along with mechanised handling systems envisage the capability of FCI to ensure food security by various benefits such as good preservation of grains, reduction in losses, sufficient bulk storage capacity, low operating cost, effective handling and excellent quality control of food grain. Handling and transportation infrastructure is improved by links of integrated rail and road facility. This modern technology silo projects made farmers self-reliance by providing better procurement facilities, leading better financial gain. The automated technology has provided sustainable and efficient solution by reducing the operating cost and laborious work. This strategic decision had demonstrated to the commitment by Government of India for ensuring nation's sustainable food security ecosystem [20].

5 Types of Silos

Based on geometry, silos are classified as flat bottom and inclined bottom silos. Based on cross sectional geometry it could be circular, square or rectangular type. In inclined bottom silos, bottom inclined part of the silo is called hopper, whereas top part is called bin of the silo [22, 23].

Table 3: Types of Silos

Type	Description	Image	Reference
Tower Silo	vertical cylindrical structure used for grain, cement, and woodchips.		[15]
Concrete Stave Silo:	constructed with small precast concrete blocks interlocked with ridged grooves, forming a robust shell.		[24]
Low Oxygen Tower Silo:	Maintain a low-oxygen atmosphere for storage of fermented materials.		[25]
Bunker Silo:	feature sturdy concrete walls, forming trenches for storing large loads.		[23]
Bag Silos:	plastic and airtight bags or tubes used for on-field storage of grains and fodder.		[26]

6 Innovative Generation of Metal Silos

At Chicago, in 1893, first metal silo was kept in exhibition. In 1914, metal steel silo was reported as useful along with application of old used oil. Today these steel silos are serving the purpose still after 100 years [27]. Metal silos are generally used for grain storages in all the sectors of agricultural products. Metal silos are generally fabricated in mild steel (MS), Stainless steel (SS) or Galvanized mild steel, etc. The cost of fabrication varies exponentially based on selection of metal. Still, it is various benefits over its life. Generally galvanized steel sheets are used for silo manufacturing. These silos can be fabricated in various shapes like cylindrical, square, rectangular, etc. These galvanized steel silos are having better life due to corrosion resistance layer of zinc on steel. Additionally, these silos are also painted with special grade aluminum paint. This ensures the better protection of metals from extremely severe climate conditions. [7, 9]. This also improves the appearance of silo. Throughout the years development in silos had taken shape from riveted silo, welded silo, and assemblage silo to spiral silo. Originated from the early 20th century, it has history of more than 100 years. Steel silos were widely used in western regions of the world for grain storage. The generation silos are broadly classified in three generations.

6.1 First Generation Silos: In the late 20th century, these silos are the product of Initial Rapid Development of the Industrial Revolution. The silos were made up of cement concrete or riveted steel joints. These silos are small in sizes and have limited usages because of technical issues [13].

6.2 Second Generation Silos: Second generation steel silos had taken major change in design of silos and do these silos are also known as assemblage steel Silo (ASS). It is basically manufactured with hot deep galvanized steel sheets. Also, the standard parts can be replaced easily. This can extend the service life of silos. These silos can be transferred from one location to another location making it ideal for variety of grains and locations. All this ASS silos has been provided with latest improved technology and design for specific use and specific agricultural products [28].

6.3 Third Generation Silos: The third-generation silos emerge as a revolutionary milestone. These silos are also known as Spiral steel silo (SSS). This silo comprises advanced technology and special equipment for construction. During rolling process for manufacturing silo, exterior part of silo is made to a spiral convex. This spiral convex band has five times more thickness than the material thickness. These silos are more stable and high strength over the other types of silos [29].

7.0 Benefits of Grain Silos:

Silos for grain storage are advantageous in many ways:

Reduction in Losses: Due to sealed design, the grain silos, the losses of grain found minimal in all types of seasons [30].

Increased Capacity of grain storages: The capacity of grain storage is tremendously increased compared to conventional storage due to its tall structures [31].

Enhanced Preservation of grains: By using modern automation techniques of inside parameters of grain, it is possible to maintain consistent quality of the grain [32].

Land Utilization and Optimization: Compact silos require very little area compared to conventional storage systems. This saves the substantial amount of land cost [28].

Automation and Mechanization of grain silos: Modern silos are equipped with automation and mechanization for grain loading, unloading systems lead to reduce the operating cost [33].

Bulk handling of grains: The bulk handling capability of grains in silos provided cost saving by eliminating costly bags. Also save the laborious activity associated with cleaning, handling, packing, weighing and dispatching of the grains [29].

Storage efficiency and Sustainability: Automated technology drastically reduced the losses, operating cost with extended shelf life and thus further improved its storage life and enhanced the overall storage efficiency. This efficient handling, storage, and waste minimization promotes the overall sustainability of the food grain by minimizing the environmental impact [26].

Hence all the benefits of silo usage are tabulated below table No. 4.

Table 4: Tangible and non-tangible benefits of silos verse conventional storages for grain

Benefit Type	Modern Grain Silos	Conventional Storage	Reference
1. Reduced Losses	2–5% (scientific control)	10–15% (rodents, moisture)	[30]
2. Space Efficiency	Vertical design; uses less land	Large land footprint required	[15]
3. Labor Efficiency	Mechanized loading/unloading	Manual	[5]
4. Turnaround	3–5 times faster movement	Slower grain handling	
5. Accuracy	Digital monitoring (IoT, sensors)	Manual records; prone to error	[34]

Along with various benefits of the silos, potential challenges are illustrated in Figure 4. Silos are proven as a backbone in modernizing granular storage facilities and address various challenges pertaining to traditional storage methods. Grain silos have become essential in addressing these challenges by ensuring long-term preservation and distribution of grains.

**Figure 3: Potential Challenges for the silos for Agricultural products**

8 Technological Advancement

The modern silos are associated with automated techniques, testing, plant design and mechanized handling systems [35]. High quality of storage needs monitoring, control and human intervention to maintain quality. This is very laborious and risky activity [3]. Hence to control storage parameters and environment inside the silo, automation employment is needed of time [36]. It is primarily used to control various parameters affecting on quality of grain like air temperature, humidity, pressure, moisture content of grains, insect infestation, carbon dioxide and methane. All these parameters must be controlled and monitored to reserve the grain storage for long term and its optimum shelf life.

This automation is also important from safety aspects. Research has developed smart devices for specific storage of grains. Various types of sensors are available for detecting and controlling the above environmental parameters. The critical limitations are high capital cost, data integrity and security and lack of operational knowledge to the farmers.

9 Failures of Silos

The frequency of silo failure is too high compared to other industrial equipment. Failure includes distortion or deformation to complete collapse. These failures are generally occurring due to common operational and design mistakes. Each year, several silo failures occur in entire world with some degree of accidents. It may involve cracks in concrete wall, dent in steel, corrosion issues, etc. [37]. The cost of silo failure is having severe impact on cost of lost. This involves loss of production capacities, repairing cost, significant danger to human in the vicinity of failure, litigation issues to the designer and manufacturing agency, etc. The silo failure causes can be categorised as: design, construction, usage and maintenance type. [38]

9.1 Failure Due to Design:

As mentioned earlier, silo design is important aspects and must considered the characteristics and properties of material, silo geometry, static pressure and dynamic load. While designing, the self-vibrations, rat holing to be considered for stable discharge. The effect of fabrication, non-uniform and thermal loads must be considered. Special consideration must be provided for temperature, moisture, self-heating. While designing, the effect of external factors like, extreme weather conditions, earthquake and natural calamities must be well considered to avoid failure [37].

9.2 Failure Due to Construction:

In construction or fabrication stage utmost care and discipline must be followed. Poor workmanship and faulty material are two major causes of failure in construction phase. Inadequate steel usage and uneven foundation settlement are common problems in silo failures. Change in design during construction phase also led to probability of failure [37,39].

9.3 Failure Due to usage:

Particularly well designed and properly constructed should have very long life. Unfortunately, it doesn't true for all times. But sometimes due to change in material properties, wear and tear due to corrosive environment, explosion inside the silo may lead to failure. Dynamic loads due to arches, rat holes are major causes for silo damage. Self-induced vibrations and explosions can also cause damage to silos [38, 40].

9.4 Failure due to change in flow patterns:

If source of material changes than considered for design may lead to damage. This occurs due to different in flow properties and material characteristics which may provide adverse effect against design considerations. This has generally occurred when the silo is designed for mass flow and in silo funnel flow occurs. Or vice versa of flow pattern may also cause damage to silo. As in both flow modes the wall thickness may differ to cause damage to silo. Buckling of unsupported walls are common problem of silo failure [37, 41].

9.5 Failure due to improper maintenance:

Proper and periodic maintenance of the silo should not neglect, as most of the silo failures are due to lack of regular preventive maintenance. Periodic inspection and repairs of silo walls, ancillary equipment protect the silo for long life. It is reported that, invisible damage in thickness of silo due to corrosion and erosion is main causes of silo failure. Unskilled manpower with lack of knowledge of proper maintenance also leads to silo failures [38].

Hence silos with well designed, properly built, efficiently operated and periodically and proactively maintained silos will provide long life. This all aspects reduced the cost of repairs and rebuilt, cost of litigation. [42].

Various accidents are also reported in silo. Grain entrapment in silos occurs when a person submerged in grain and not able to come out. Also, due to sudden grain collapses, person found buried inside the silos causing entrapment. When victim completely buried inside the grains called as engulfment. It has very high fatality rate. The best solution to prevent grain entrapment is no entry inside the silo. But is not practical. Hence by providing proper safety precautions, proper ventilation and inside infrastructure for movement, entry of trained and skilled persons can be provided. Periodic training needs to be provided to all workmen for entry and rescue operations. A simulator for grain entrapment is generally used for training and education of entry and rescue operations [43].

10. Gaps in Current Research and Recommendations for future Development

Each phenomenon occurring in the grain silos cannot be explained with the help of current knowledge. The in-depth research on silo is an essential for transformation of innovative knowledge into engineering applications. From the foregoing discussion, necessary measures must be taken to improve, modernise and mechanise the grain storage. And hence wastage of grains needs further attentions to minimise the same. Strong policies and governance frameworks are needed to support sustainable food security initiatives. For achieving this, it requires coordination among business, government, society, civil and individuals etc.

Research needs to focus on multiple facets of silo operation to accelerate and utilise the effectiveness of use of silos. This review further suggests areas for further research in automation. Understanding the unique needs of different granular products and developing solutions tailored to specific granular materials is important key part in optimizing silo usage worldwide. Interdisciplinary research and technology transfer between chemical, agriculture, food, mechanical, civil and automation are necessary to realize these benefits globally.

11. Conclusion:

This article tried to put comprehensive aspects of silos usage for grain storages comprising more diversified approach to grain storage. Production facility, consumption scenario are directly related to population dynamics, employment issue and poverty. Investing in modern, well-maintained silo infrastructure is vital for maximizing the benefits of silos to accelerate sustainability development in emerging economies. Cause for damage of silos, explosion and its prevention are reviewed. Soil quality, design considerations for

foundations, earthquake, explosive nature of contained material, corrosion of metals, concrete deterioration, ratcheting due to thermal effect, are major factors for silo failures.

This review is unique because of the consideration of all aspects for the engineering to develop silos with essential tools and strategies. This will enhance agriculture ecosystems sustainably. Innovative technology will provide better and safe storage facility to reduce losses and enhance resilient supply.

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