

Modern Silo for Grain Management: A Critical Imperative for Sustainable Food Security Ecosystem.

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Abstract

Food security is always worldwide major concern, and the consequences of food insecurity have harmful effects. About 10% of food is lost after harvesting due to poor storage, pests, rodents, and microorganisms. Reducing these losses is a sustainable solution to reduce loads on natural assets, get rid of famine, and improve livelihoods. In world, more than 2.3 billion tons of grains are produced on annual basis. But factors like the pandemic, natural calamities and wars have significant effects on food security and grain production. Effective management and monitoring can enhance stored grains life. This review discusses current issues, potential challenges, and future perspectives related to grain storage. It explores modern silos to extend the shelf life of grains, enhance food security, support farmers, and protect ecosystems. The article also examines the techno-commercial aspects, providing insights for policymakers on the feasibility and viability of future projects. Gaps in the current literature are highlighted, suggesting areas for further research. Recommendations are pointed out for future developments in automation, Internet of Things (IoT), and artificial intelligence.

Keywords: Modern Silo, Grain Management, Food Security, Sustainable, Ecosystem.

1. Introduction

Storage of granular materials in silos are subject of interest for both industrial applications and academic curriculum. A lot of inventions in silos have been done since the industrial era. Silos are widely used in various industries and in agricultural sector for conservation of materials like food grains, cereals, ores, sugar, flour, cement [1]. Food security and sustainability is a growing concern, and the consequences of food insecurity have harmful effect [2]. About 10% of food is lost after harvesting due to the poor storage, pests, rodents, and microorganisms [3]. Reduction in these losses can help to reduce load on natural resources, to get rid of famine and improve livelihoods safeguarding the ecosystems [4]. Re-evaluation of traditional grain storage structures in terms of ecosystem and sustainability is important [5]. In current scenario, conservation of biodiversity in form of grain storage is critical part of ecosystem [6].

Tremendous changes in agriculture landscape and growing demands of modern industries, have necessitated modern grain storage facilities [7]. This review discusses current issues, potential challenges, and future perspectives related to grain storage. An overview of various innovative storage systems and their effectiveness in preserving food grain have become a vital part. This review explores innovative designs to extend the shelf life of grains, enhance food security, support farmers, and protect ecosystems. Accidents in silos may lead to serious consequences. The root causes of all accidents typically from environmental factors, operational hazards, structural stability and nature of material. Thorough understanding of accidents with their scientific reasons can provide to enhance safety measures. Silo collapses due to faulty design, construction or deterioration of structure are led to accidents [8]. This review addresses challenges of fire hazards, and safety concerns [9]. The article also examines the techno-commercial aspects of grain silos, providing insights on feasibility and viability of the grain storage operation [10]. This will help the leaders in various sectors for strategic initiative to obtain sustainable agricultural goal. Negligible attention has been given to this critical area.

More research work is needed to optimize the use of silos for industrial applications. There are several challenges related to flow through silo, silo design, and its operational safety. To enhance the effectiveness of silos usage, research needs to focus on multiple facets of silo operation: flow dynamics, behaviour of material, environmental aspects safety and automation. To vanquish this challenges, innovative design concepts and integration of advanced simulation techniques like computational fluid dynamics, Discrete Element Method and better sensing technologies are essential. This review suggests various areas for in automation [11], Internet of Things (IoT), energy efficiency, and application of artificial intelligence [12].

2. Global Agriculture Scenario

Drastic increase of urbanization, sudden climate change and land uses excluding agriculture, have resulted into concerns. The present population of entire world is 7.7 billion. It is projected to increase drastically up to 9.7 billion in next 25 years [13] resulting in tremendous increase if food demand. In developing countries, popular grain products are heat, rice, maize [14]. Knowledge inadequacy and lack of smart storage facility led to food losses. [15]. The expected population growth is plotted in figure 1 [16].

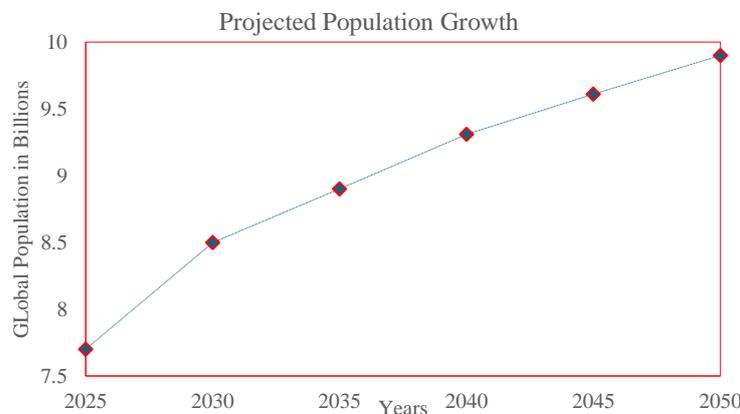


Figure 1. Global Population Growth since 2025 to 2050. [16]

The global sector is agriculture is moving towards sustainable intensification. Its main aim to provide sufficient food to peoples. Also, reduction in emission is a major concern, as one third of the green houses emission is only through agriculture sector. Hence increase production is going to become dominant. Climate change, The global agriculture sector is shifting toward sustainable intensification, driven by the need to feed 9.7 billion people by 2050 while reducing emissions, as agriculture currently causes one-third of global greenhouse gases. Productivity-led

growth is becoming dominant over land expansion, though climate change and input costs (fertilizer/energy) present significant risks to future stability. The cereal grain production in top 10 countries is presented in figure 2.

The agriculture market is exponentially increasing with projected size of current approximately 13 trillion USD to 18 Trillion by upcoming 2030. This can be achieved only by utilising modern silos and digital agriculture. Whereas Indian agriculture market is approximately 450 billion USD in 2024 and is projected to increase up to 737 billions by 2034. Global silos market is expected to increase to 299 mUSD (million US dollar) by 2034 from ~210 mUSD in 2024 [17]. Raw material management and effective storage facility are essential to drive the market of silo. In regions like Ukraine, these grain storage plant systems not only safeguard vital seeds but also contribute to a broader global impact.

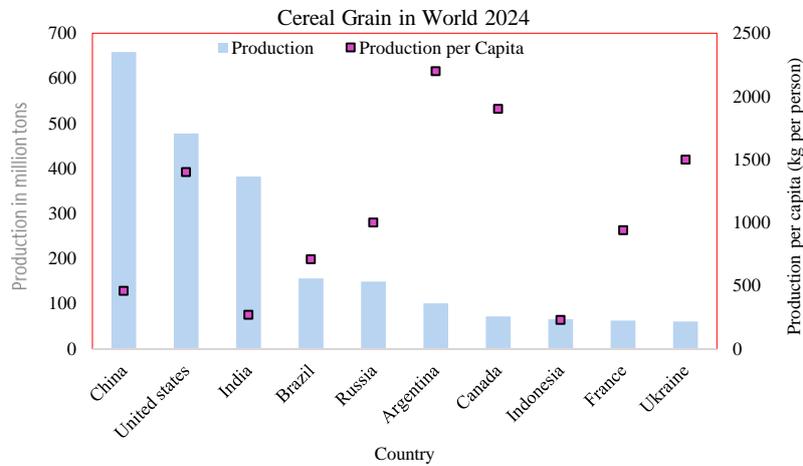


Figure 2. Cereal grain production in world. [18].

In 2015, United nations had adopted Sustainable Development Goals (SDGs) for 2030. The motivation is to provide peace as well as prosperity for the peoples on the planet. The moto is to address the global challenges such as zero hunger, poverty, climate change and inequality etc. To overcome these issues 17 goals are set to complete by 2030 [19].

In India, losses of grain are affected mainly by factors like biotic and abiotic. The losses in various crops like cereals, pulses and oilseeds are reported to be about of 4.5 %, 5.0 % and 6 % respectively. Due to this losses, various inputs (land, water, seeds, chemicals, energy etc.) used for production of grains are also consumed. Main purpose of grain storage is to maintain the quantitative and qualitative nutrition value of grains [20]. Hence grain storage technologies used in silos can drastically reduce grain losses. The silos play vital role for three important end users in India: government, farmers and manufacturing Industries [21]. Indian farmers are using traditional storage systems for storage of grains. The cereal production in India since 2002 to 2024 is presented in Figure No.3. [1]. Storage of food grains in silos has gained momentum in India and it can help the country to overcome huge losses from poor storage facilities.

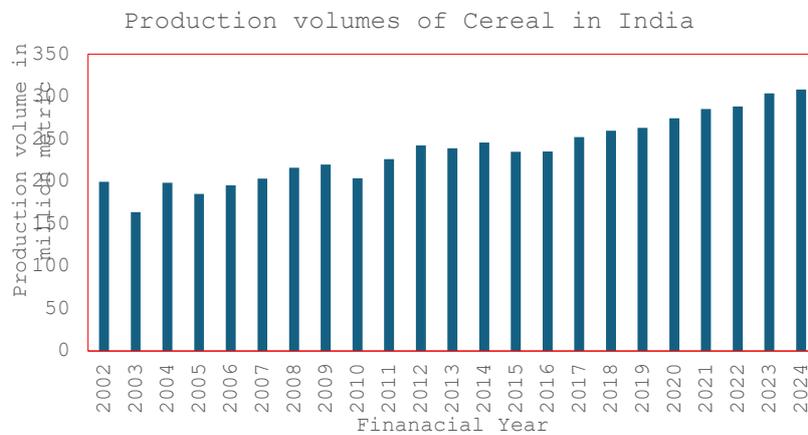


Figure 3. Production volume of cereals in India from financial year 2002 to 2024 [1].

3. Silo: Basic Concepts

Silo is a widely used equipment for the storage of granular material. The main thing is to securely be storing the material for it extend life. The ideal silo can be considered as equipment having capacity of maximum quantity on minimum floor area with regular, reliable and consistent flow. However, several problems are regularly occurring in terms storage like segregation, flooding, caking as well as discharge problems like rat-holing, arching, deal zone formation. It may also lead to self-heating, accidents and explosions, etc. [22]. The modern silos are provided with various mechanisms to feed from the agriculture land and to transport at marketplace. Hence silo system comprises of the total ancillary equipment i.e. silo structure, conveying system, feeding mechanism, discharge mechanism, instrumentation, automation, quality check measures, safety interlocks and explosion proof systems. The Flow of granular material through silo is a subject of interest to researchers, academics and industrialists [23]. New dimensions in this field have taken shape of design features in this area since industrial era. Though silo seems simple equipment, several design criteria must be considered for its design and operational features. For granular solids gravity force is dominant with respect to inter particle interactions. This design generally includes prediction and modeling of different flow patterns, velocity profiles, exit flowrates and residence time distribution (RTD). Based on silo geometry and properties of granular material, flow can occur in two different modes: mass flow and funnel flow [7]. In mass flow, at every location in the silo, the entire material is in motion during flow. Hence there is no stagnant material and flows the material in first in first out (FIFO) pattern. This mass flow indicates stable, controlled and predictable flow. This flow does not form dead zones and has low wall friction. But it needs higher capital cost for smooth walls and specific design of bottom hopper and discharge mechanism [23]. Funnel flow generally occurs in flat discharge or very low sloped conical

bottom and non-smooth of walls. The material flows through central part surrounded by stagnant material on the wall. Thus, flat bottom silos provide maximum capacity on same floor space but exhibits funnel flow. This funnel flow is having issues of arching, rat-holing and dead zone formation. It also having issues of settling, caking, flooding and segregation. Collapse of rat-hole may lead to damage to silo due to unpredictable dynamic load. Hence to overcome rat holing, the opening of the hopper must be equal to the critical rat hole dimensions. But it is impractical to make silo of larger dimensions. To overcome the issues of funnel flow, expanded flow fulfills the requirement by combining funnel flow and mass flow patterns [24]. It consists of funnel flow at the top section and mass flow at the bottom section. This creates expanded channel of flow at bottom to prevent rat holing at the top part. Generally, this expanded flow design is used in large silos for agricultural non gradable material, which has proven cost-effective design, where mass flow is not practical i.e. for large scale bulk storage. The concept of expanded flow is also beneficial for silos with multiple outlets. The different types of flow regimes are shown in figure no.4 [7].

4. Journey of Silos

Modern Silos cannot be completed without mention of its overall journey. Civilization and Farming development started around 10,000 B.C. It is reported that cultivation of wheat, rice, and corn barley were started in 3500 B.C. Underground pits were used for storing grains. Evidence was discovered by archeology. Various Philistine houses with stone structures for grain storage dated 1850 to 1750 B.C. were discovered [25]. Around 318-272 B.C. during period of King Pyrrhus, silos were used to preserve bean and leguminous grains. In Greece, Caverns were utilized to store grain. It was divulged that some grains were in good condition after storing them for about 220 years. Varro, a roman scholar (116-27 B.C.) mentioned that Pits were used to store grains for 50 years and millets for 100 years. Pliny (23-79 A.D.) observed that in Greece and Turkey, corn was harvested and preserved in trenches called Siros. In southwest Iowa, silo pits were discovered by students of archeology of 10th centuries, which were used for winter storages. In France during 1707, huge quantity of grain was discovered, which was stored in 1528 [26]. It was in good condition though kept more than 200 years. Also corn stored in silo in 1591 were found in 1828 i.e. after 235 years. In 1873, Hatch built a first silo in America. He was later awarded in 1918 for his leadership role in agriculture. In 1877, Snyder built an above ground stone silo in square [27]. In 1888, John Steele built first round silo lasted for 27 years. In 1893, steel round silo was exhibited in Chicago and later 1898 largest ever silo (64 feet diameter and 60 feet height) was erected. A tremendous amount of revolutionary development was carried out in silo from 1885 to till date. During 20th Centuries, various types of materials are used for construction of silos such as wood, tile, tile-staves, steel, glass lined, monolithic concrete, concrete staves and metal silos [28].

First ever silo of metal body was used in 1893 at Chicago. Then it was used for oil storage in 1914. After so many years, still it is serving the purpose. [25]. Steel of different grades are being used to fabricate the silo. The silo may be in different shapes i.e. rectangular, square, cylindrical, flat bottom, conical bottom etc. The galvanized sheet provides better life due to layer of zinc. Also, gal volume material is used to further extent its life. Nowadays aluminum painting is used to avoid corrosion from severe climate conditions. [14]. 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. Latest spiral steel silos emerge as a revolutionary change in silo usage; spiral convex band provides more strength and stability over years. Silos are bunker silos, tower silos, concrete stave silos and low oxygen tower silos.

5. Advantages of Silos:

Modern grain silos represent a major vault for the efficient management of grain supply chain. This facility is comprising of new technology with automated bulk handing facility for smooth movement of grains [11]. Hence essential commodities can be stored and transported efficiently throughout the world. The aim of sustainable and technology driven silo facility is to improve food security, reduce waste and ultimately improvement in live hood of millions of farmers [29]. Silos proved as ideal mode of storage for buffer stock of grain products and its food security. Hence all the benefits of silo usage are tabulated below table No. 1.

Table No. 1: Advantages of different types of silos with detailed explanation

Type of Advantage	Description	Utility	Reference
Reduction in Losses	Due to sealed design, grain quality is maintained.	Help farmers to keep grain for long time	[30]
Bulk handling of grains	Cost saving by eliminating costly bags and labors.	Reduce laborious activity associated with operation	[31]
Extended Shelf Life	Maintain required conditions inside the silos	Grains preserved with quality for very long time in years	[13]
Protection from weather, pests, rodents	Silos are hermetically sealed and airtight, preventing entry of insects, rodents, etc.	Reduces wastages, losses from contamination	[32]
Land Utilization and Optimization	Stored very high quantity in vertical	Silo can store grains in multiple times than other traditional method.	[33]
Enhanced Food Security Ecosystem	The extended shelf life and long-term preservation in famine area.	Food security by utilization in famine areas.	[5]
Storage efficiency and Sustainability	Improved storage life, overall efficiency and sustainable products.	Help for cost stabilization and profit gain during market fluctuation.	[3]

6. Modern advanced Technological Development in Silos.

Recent technological advancement in silos for grain storage has gained momentum to overcome losses of grains. [7]. The industrial revolutionary in this field is an imperative of time. Researchers, scientists, engineers, industrialists and farmers must collaborate in latest technological development through dissemination of information by their own experiences. It is primarily used to control pressure, moisture content of grains, insect infestation, gases like carbon dioxide, methane, discharge flowrate, temperature and [11] as shown in figure 4.

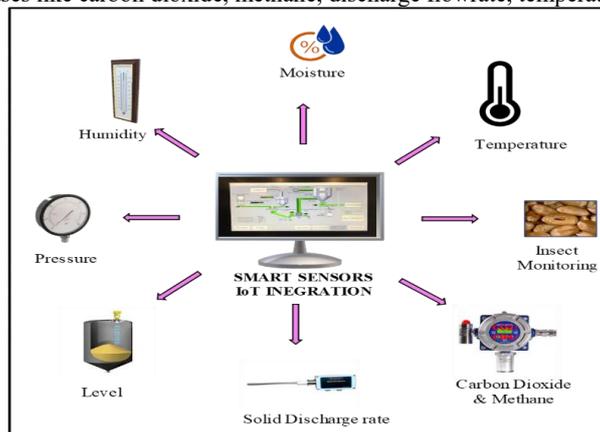


Figure 4. Smart sensors with integrated IoT for measurement, monitoring and Control of various parameters.

For long-term storage, these parameters must be controlled. The automation also helps to reduce operating cost of silos for agriculture grains [30]. Smart sensors along with internet of things (IoT) are useful to enhance storage of grain products [34]. Though IoT has great scope, it has various limitations. It needs special policies, data encryption system and trained personnel for operation of smart silos systems [35]. Schematic mechanism of automated silo with IoT and AI is shown in figure 5.

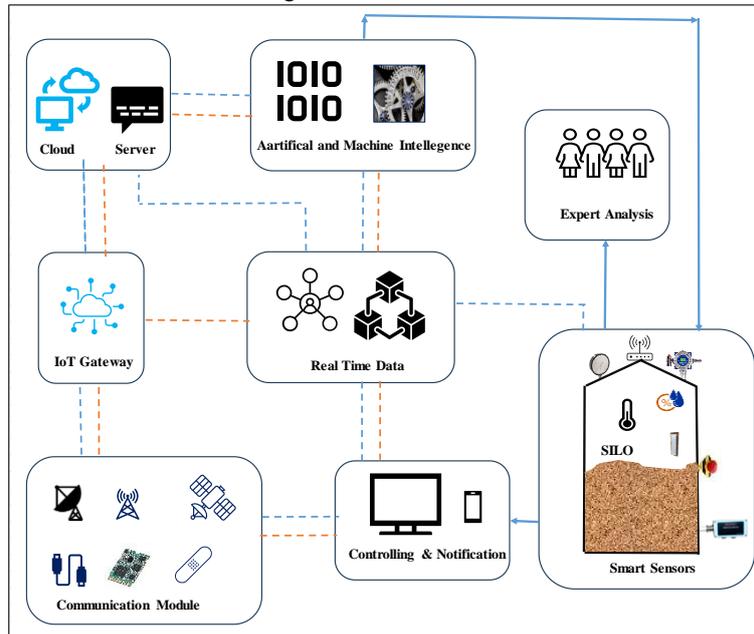


Figure 5. Automated Silo Control System comprising IoT and AI.

AI consists of smart sensors [34], IoT, precise sensing and prompt transmitting of data with immediate outcome. This leads to further advanced automation technology, widely known as Internet of Things (IoT). Hence IoT based AI [35], and digital technologies have potential to provide innovative modelling of silos for grains. Hence Automation with AI and IoT have tremendous scope to resolve issues of weather condition, pest detection, insect infestation, real time data pollution and radiation, etc. Hence It assists to the farmers for better control on operation of silos and grain product storages for long lifetime with ensured consistent quality [6]. Hence automation using AI and IoT are very beneficial to farmers for continuous uninterrupted monitoring and control of stored grains though having huge capital and operating cost. Financial support to farmers, digital literacy for usage of automation and secure data encryption are the major concerns. This would help with the implementation of automation on wide scale [35].

7. Architecture of AI with IoT ecosystem In Modern silos.

IoT and AI mean two sides of same coin. IoT devices are comprising of multiple devices to communicate effectively with communication modules. Any change in parameter signal is sent or received by sensors. The data (Real time) will be sent to remote server or cloud through an IoT gateway, where data management is done in database. In AI-enable data is generally taken by analyzing programs, where data cleaning like outliers' removal, normalizing etc. is carried out. Number of algorithms are applied to the data. A model is generated to check the accuracy of data. Validation is being used to check the stability of model. Estimation of quality of model is performed by using recall values. It is then deployed to the cloud. Based on the incoming data, AI model generates and predicts intelligent decisions. This is then communicated for required operation and to the farmers/applicators through smart phones in simpler understandable results. The notification in the form of email, short message service are provided. Mobile applications are found also useful for user-friendly operations. Integration of AI with simulation technologies are also available and broadly categories as: Digital Twin System [36]; Edge computing Technique [37]; Blockchain Mechanism [38] and Robotics and extended reality [39]. Electronic nose, electronic tongue [40] and electronic eye system as a game change in the advanced technology. The innovative system to interconnect both simulation and automation is an imperative of time. In digital twin model is defined as the virtual model created which continuously mirror the real silo behaviour. This can be possible by real time data of sensors [34], physical based simulation to predict, temperature, airflow and grain behaviour. The digital twin integrates all this to provide efficient and effective results [36]. The parameters like moisture, temperature, and level of grain received from real sensors are fed to simulators. Based on the inputs, the automated system controls the aeration [41], outlet rate and starting of vibrators to avoid clogging. This is called digital twin of the silo [36]. The Modern silos for different application and with specific technique are tabulated in table 2.

Table 2. Different aspects of smart silos.

Smart Silos	Application	Reference
Real time Digital Twin	Modeling of air flow, Structural monitoring, IoT data integration, Cloud based simulation platform.	[36]
Self-cleaned antimicrobial	UV sterilisations units, Ani microbial nano coating, Automated robotic cleaning, Dust removal system	[39]
Clog prevention	Acoustic sensor, Vibration sensors, Load cells, Flow emerging	[42]
Renewable energy powered	Solar panel, Thermal energy, Wind power, Energy efficient aeration fan	[41]
Blockchain traceability	Sensor based grain quality monitoring, Automated digital record Supply chain transparency	[38]
Acoustic pest detection	Sensors for early infestation (pesticide free storage), Weather prediction dynamically, Early detection benefits	[34]
Climate adaptive	Control of air based on climate change	[41]
Robotics grain inspection	Camera, gas sensors, mapping system to detect structural cracks, grain bridging.	[39]
Intelligent multi-storage modular	Can store different grain simultaneously, prevents cross contamination, better inventory control	[35]

8. Current Issues, Potential Challenges and Future Perspective in Silos:

8.1 Current Issues:

In Silo, numerous ongoing issues are faced and reported. Global issues in silos for grain storage needs to be properly considered during design phase only. Silos are often faced issues to maintain required humidity and temperature inside the silo. This impacts on moisture content on grains. In warm and humid climate, insects, rodents, fungi are creating persistent challenges. These current issues are tabulated in brief in following table 3.

Table 3: Current issues in silos with their effect and reson

Current issues	Effect	Reason	Reference
High Capital Investment	Less adoption of silo by farmers	High cost of civil, steel, land, Automation	[43]
Power Fluctuation	impact on aeration, ancillary equipment and automation	Gap between Power generation, and excess consumption pattern.	[30]
Ideal or under use of silo	Its effects on payback	Improper management of procurement and seasonal arrival.	[44]
Improper operation and poor maintenance	It leads to spoilage of grain	Lack of skilled manpower and irregularity in maintenance	[45]
Dealy in regulatory approvals	Dealy in commissioning and startup activates.	Lack of coordination and communication of agencies.	[22]
Specific Design for single grain	Non flexibility of variety of grains in different season	Non consideration of variety of grains during design	[23]
Extreme climate change impact	It may impact even on silo structures.	Improper design consideration for severe weather conditions.	[13]

8.2 Potential Challenges:

There are numerous challenges occurred for successful implementation and sustainable operation of silos. This challenges broadly classified as:

Strategic Challenges: Site selection for installation of silo is difficult task. It needs prior investigation on soil condition and easy access. For small land holders, it is always challenge as silo system needs bulk and continuous supply of food products to avoid underutilisation.

Operational Challenges: Silo needs periodic fumigation. If this cycle is not properly followed, pest and insect infestation become major challenge. Also skilled manpower is important from automation and maintenance point of view. Real time monitoring of various parameters like moisture content, humidity, temperature, pressure, oxygen, carbon dioxide and methane concentration, fill height, are needed to maintain quality. Also, during discharge, clogging and bridging effect may occur and needs system to break the clogging.

Technical Challenges: Moisture content, humidity, temperature, pressure, oxygen, carbon dioxide and methane concentration, fill height, etc. must be maintained for specific grain. Failure of this may lead to spoilage of the grain products. Malfunctioning of accessories along with silos like material handling systems, sensors lead to breakdown.

Financial Challenges: Capital cost for installation of silo is very high. Hence financial support must be considered. Market fluctuation in rates, natural calamities, may impact on profitability and hence payback of the silo. Hence feasibility of silos for small farmers is a big challenge. And need proper feasibility and viability study by cooperative approach of farmers in the same region.

Regulatory and policy: Statutory approval procedures for land acquisition, construction, environment, safety, utilities may affect directly on the feasibility of Silo. Hence uniform policies, uncertainty of market rates, rules for procurement, contractual agreement, role of public and private entrepreneurs needs to be properly evaluated.

Environmental Challenges: Sudden change in climate is a big challenge. It affects to maintain stable parameters inside the silos. Power failure is also impact on working of ancillary systems like elevators, conveyors, sensing instruments etc. Natural calamities and disaster like flood, earthquake, cyclone may lead to severe damage to silos.

Quality and safety challenges: Lack of periodic cleaning, proper hygiene, may lead to damage the grain products. To maintain the quality of grain, parameters like moisture imbalance, fungal contamination, rodent infestation to be properly monitored and controlled. To remove the clogging inside the silo is very dangerous and proper precautions needs to be taken to avoid grain entrapment, confined space hazards. Proper scaffolding arrangement to be provided for working at height. Excess overloading may generate stress on the structure and walls and leads to damage and even collapse of silos.

8.3 Future Perspective:

Grain silo is emerging as game changer. It has played a critical role in food security, sustainable approach, ecosystem, climate change, agrotech logistics. In coming years, grain silo evolves with drastic change in infrastructure, technologies, policies, and practices. A traditional storage system is inadequate for handling high grain production. Automated climate-resilience silos are proved to prominent solution to minimise issues and year around availability. Hence demand for modern silos will outpace the conventional silos.

Silos will become a part of smart agriculture and climate resilience plans for food security. Silo integration with smart technologies is going to reduce losses and to maintain the qualitative and quantitative supply of food grains throughout the years. Hub and spoke model in logistics i.e. integration of silo terminals with container, rails, trains is going to provide faster, safer and cost-effective grain movement.

Public- Private partnership will play an important role in scaling a big silo capacity worldwide. Future silos will also be operated by using solar powers. These silos will be constructed by using green material and technology. Hence future perspective trend will involves move from centralisation to decentralisation of smart silos of small capacities. This will enable storages at the grass roots to reduce losses.

9. Techno commercial Feasibility and Viability:

In view of the complexity of silo design, it always remains a challenge to develop simple, safe, compact and economically feasible silo. It involves analysing both the technical and commercial factors related to their design, construction, operation, and business viability [46]. Based on the application, different types of silos are used. Selection of the silo is important from its technical suitability and viability for the grain [47]. The design consideration must be considered for its capacity, material handling systems, automation, aeration systems if required, fumigation systems, civil construction philosophy for its foundation and structural integration [44].

Commercial aspects of silos involve capital investment (Capex) related to silo: civil cost, machinery, related utilities, instrumentation and automation [43]. The capex can vary widely based on the location, climate condition and scale of storage. Operating cost (Opex) generally involves power consumption, preventive and predictive maintenance, labour and supervision and other operating cost like pest control fumigation, insurance, regular statutory compliances etc [1]. The revenue basically involves various taxations, government policies for subsidies, trading profit and fees related to private operators for grain storages. Based on the capex, Opex and revenue of any silo project, payback is of 3-7 years [48, 49]. This payback purely depends on capacity utilisation, operating expenses and price of grains. It varies drastically due to grain spoilages, changes in regulatory compliances. The techno-commercial aspects of grain silos are tabulated in table 4 for granular material like wheat, maize, rice, soybeans, pulses [2, 6].

Table 4: Techno-Commercial Comparison for different granular products in silos.

Criteria	Wheat	Maize	Rice	Soybeans	Pulses	Reference
Recommended Silo	Flat bottom,	Hopper bottom,	Flat bottom,	Hopper bottom	bag silos	[24]
Moisture Sensitivity	Medium	High	High	Very High	Poor	[4, 6]
Grain Flowability	Good	Good	Poor	Moderate	moderate	[50]
Capital Cost Lacs per 1000 ton	100-150	120-160	130-180	140-200	120-170	[17,32]
Payback Period in Yr	4-5	4-6	5-7	5-7	5-6	[48, 49]

This table helps in evaluating suitability, cost, and other parameters for silo selection and planning. Sensitive grains like soybeans or paddy needs higher costs for due to their moisture sensitivity and higher aeration needs. Grain silos are a technically feasible, financially viable, and strategically essential solution for improving grain storage in entire world [50]. Their success depends on High utilization rates, Effective management, Long-term contracts, Government support and incentives. Modern grain silos offer a technologically robust and commercially viable alternative to current aging food storage system. This structured analysis of the feasibility and viability of grain silos, with a focus on technical, financial, operational, and strategic dimensions will help for optimisation of silo to improve food security, reduce post-harvest losses [44].

10. Gaps in Current Research

Despite various powerful tools, the combination of physics of grains and engineering of silos is still in infancy. Bridge among branches of technology and engineering like fluid mechanics, tribology, statistical physics, surface chemistry, entomology, biotechnology, structural and civil engineering needs to be built. Research needs to focus on scientific storage facilities, to develop management protocols for secure and safe design of silos. Strong policies and governance frameworks are needed to support sustainable food security initiatives globally. To achieve sustainable food security requires collaboration among governments, businesses, civil society, and individuals.

11. Conclusion

In the context of sustainable and secured storage systems, modern silos are proven as the imperative aspect. Modern silos play a crucial role in modernizing granular storage facility and addresses challenges related to traditional storage methods. The scientific and technological innovation in the modern silo system is going to emerge as a new era. It is emphasized that coordination, cooperation and communication among various application industries, government organizations, non-government organizations, manufacturers and farmers is the need of time for technologies-based silos for specific grain.

The article attempted to address various aspects of smart silo to utilise the benefits for sustainable development in emerging economies. These findings are unique because of the consideration of all aspects to develop system with essential simulation tools and automation strategies. This will enhance food security ecosystems sustainably to enhance resilient supply.

Digitalisation technologies and its adoption for storage monitoring are emerging as a game changer in this sector. Significant contribution is demonstrated by smart silos in food security ecosystem. Modern silos along with automated farming equipment, irrigation techniques, pest control systems, specific fertiliser usage is inevitable. The integration of simulation techniques and artificial intelligence in modern silos has proven revolutionary change in grain storage management, leading to food security ecosystem.

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