

Organic preservatives for cereal grain storage: Mechanisms, nanoencapsulation advances, challenges, and future prospects – an update

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ABSTRACT

Post-harvest grain loss by fungi, bacteria, insects and oxidative rancidity remains a major threat to world food security. The use of synthetic preservatives (propionates, benzoates, sorbates, sulphites) to preserve stored foods is longstanding; but evidence of some of these compounds' carcinogenicity, allergenicity and persistent environmental residues has recently stimulated interest in organic alternatives. This review provides an integrated appraisal of the literature on organic preservatives (mainly essential oils) used in the storage of cereal grains over the past 25 years with regard to their antibacterial, antifungal, antioxidant and repellent properties, and recent advances in their nanoencapsulation and other formulating techniques. Some organic preservatives such as thyme, clove, cinnamon, oregano oils target microbial cells membranes, inhibit the biosynthesis of mycotoxins, and repel storage pests; for instance, microencapsulated thyme oil retained >80% of its antifungal activity after six months of storage (versus <30% of unencapsulated oil), while clove oil vapours suppressed maize weevil emergence by >70% in some trials. Nanoencapsulation with carriers such as chitosan and alginate may improve the stability and efficacy of natural preservatives with minimal impact on grain quality; but high production costs, scalability, complex compositional variation, impact of food matrices and lack of harmonized international regulation threaten to limit adoption of natural preservatives, so sustained investment in R&D and harmonization of regulations will be essential to realize their potential.

Keywords: Cereal grains, Essential oils, Mycotoxins, Nanoencapsulation, Organic preservatives, Postharvest losses.

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Highlights of this paper

- The review synthesizes evidence on the antimicrobial, antifungal, antioxidant, and insect-repellent mechanisms of organic preservatives like essential oils in stored cereals.
- It evaluates recent formulation advances particularly nanoencapsulation using food-grade biopolymeric carriers that significantly enhance their stability, retention, and controlled release.
- It identifies key technical, economic, and regulatory barriers that currently limit their large-scale industrial adoption compared to conventional synthetic alternatives.

1. INTRODUCTION

The preservatives are chemicals, either synthetic or natural, that we use in cereals, fruits, vegetables, processed food, cosmetics, and medicines to prolong the shelf life of foods by protecting foods against microbes, fermentation, acidity, and decomposition (Teshome, Forsido, Rupasinghe, & Olika Keyata, 2022). Salts are used to preserve a variety of meat, like fish and hams, and jams and jellies are preserved with high sugar content (Sethi, Choudhary, & Kumar, 2025). Indians and Chinese also used spices to preserve food and preserved vegetables in salt, mustard oil, lemon, and vinegar (Ganie et al., 2022). Canning and pasteurization revolutionized food preservation in the first half of the 19th century, where the current sterilization techniques incorporate irradiation, chemical, and filtration (Anand & Sati, 2013; Knorr & Augustin, 2023).

Food safety has been a key human concern since the beginning of time. They are always refining their diets and hunts, taming animals and plants, preserving food through physical techniques and engineering molecules in food to improve tastes or prolong shelf life (Schreiber et al., 2019). Food use of technology and food additive includes key techniques to provide low cost and nutritious food, loss reduction, improvement of food quality and shelf life, and food formulation development according to market needs (Chauhan & Rao, 2024).

Food preservation is a very important aspect of the food industry, as it is a safe way of keeping food safe (Ogwu & Ogunsola, 2024). Food preservation methods, such as heating, cooling, salting, drying and the use of artificial chemicals, combined with chemical and natural (organic) preservatives, have been responsible for an improvement in shelf life (Chauhan & Rao, 2024). Chemical preservatives have been one of the earliest means of preventing food spoilage, by blocking bacteria and fungus (Anand & Sati, 2013; Bento de Carvalho, Silva, Tomé, & Teixeira, 2024); however, despite the effectiveness of these to inhibits bacterial growth and prolong shelf life, consumer safety concerns have resulted in restrictions on their use (Anand & Sati, 2013; Bento de Carvalho et al., 2024). Although most synthetic preservatives have pronounced antimicrobial activity, they have been banned because of their potential to cause cancer, resulting in a quest to find natural or organic food preservatives.

Highlights of the study: (i). The review synthesizes evidence on the antimicrobial, antifungal, antioxidant, and repellent mechanisms of organic preservatives in stored cereals. (ii). It evaluates recent formulation advances, particularly nanoencapsulation, that enhance their efficacy and stability (iii). It identifies the technical, economic, and regulatory barriers that currently limit their large-scale adoption compared with synthetic preservatives.

This review examines the potential of natural (organic) preservatives for preserving cereal grains, with an emphasis on their mechanisms of action, recent technological innovations such as nanoencapsulation, and the challenges that limit their large-scale use.

2. MATERIALS AND METHODS

Searches were conducted between January and June 2026 using combinations of the key terms above, joined with Boolean operators (e.g., "essential oil" and "cereal grain" and (mycotoxin or "postharvest loss")), and restricted to peer-reviewed, English-language publications indexed in the listed databases. The 2000–2025 window was chosen to capture both foundational work on essential-oil bioactivity (pre-2010) and the more recent

nanoencapsulation literature (post-2018), while excluding earlier pre-2000 sources whose analytical methods for essential-oil characterization (e.g., GC-MS profiling) are now largely superseded. Because this is a narrative rather than a systematic review, no formal risk-of-bias scoring or PRISMA flow diagram was used; instead, studies were retained only where methodology, sample sizes, and outcome measures were clearly reported, and findings were cross-checked against at least one other source where possible.

3. DISCUSSION OF THEMATIC FINDINGS

3.1. Cereals

Cereals are one of the most significant agricultural commodities in the world, representing the staples of human diets and the main component of feed in animal production (Pickard & McKeivith, 2005). Cereal cultivation has contributed significantly since the beginning of civilization and today represents 60% of the arable land use globally (Awika, 2011; McKeivith, 2004; Shiferaw et al., 2013). Ever-growing world demand for cereals has led to massive increases in cereal production over the past 50 years (Lal, 2016).

The major species of cereal crops are corn, rice, wheat, barley, millet, oats, rye, and sorghum (Food and Agriculture Organization of the United Nations, 2017). Despite their primary importance, cereals are easily exposed to contamination by numerous factors (soil, water, air, insects, rodents, birds, storage facilities and microorganisms). The production of mycotoxins and fungal infestation has become one of the most critical food safety concerns due to their risks on health (Bennett & Klich, 2003). Grain losses can be between 5-30% due to fungi and mycotoxins, with additional losses caused by insects and rodents, especially in the developing world (Kumar & Kalita, 2017; Mesterházy, Oláh, & Popp, 2020). Grain moisture of 12-13% and water activity below 0.70 is key to prevent the growth of microbial contamination within grains (Oluwakayode, Sulyok, Krska, & Medina, 2024; Rifna, Dwivedi, & Chauhan, 2022).

3.2. Organic vs Inorganic Preservatives

3.2.1. Organic Preservatives

Preservatives are a food additive, either artificial or natural, employed in several foods such as cereals, fruits, vegetables, processed food, cosmetics and medicines to improve the shelf life of the food by protecting it from microbial growth, fermentation, acidity and putrefaction (Teshome et al., 2022). Different types of meat such as fish, ham etc are preserved by salting while jams and jellies are preserved by high sugar content (Sethi et al., 2025). Indians and Chinese also used spices to preserve the food and also pickled vegetables in salt, lemon, mustard oil and vinegar (Ganie et al., 2022). Canning and pasteurization revolutionized preservation of food in 19th century and today sterilization is achieved through irradiation, filtration and chemical processing (Anand & Sati, 2013; Knorr & Augustin, 2023). Delivering high quality foods has been a focus for humanity throughout the ages; we have always been refining our diets and hunting skills, domesticating plants and animals, preserving food with physical methods and modifying molecules in foods to enhance flavor or shelf life (Schreiber et al., 2019). Food additives and technology play a key role in ensuring we have access to affordable, nutritious foods with reduced wastage, improved quality and shelf life, as well as developing new formulations that can help satisfy market needs (Chauhan & Rao, 2024). Food preservation is an very important aspect of the food industry as it makes sure that food products are preserved in a safe and edible state (Ogwu & Ogunsola, 2024). The development of chemical and natural (organic) preservatives alongside food preservation techniques such as heating, cooling, drying, salting and the application of artificial chemicals has considerably extended the shelf life of food products (Chauhan & Rao, 2024). As one of the oldest preservation techniques, chemical preservatives are used to prevent food from deteriorating and are successful at preventing bacteria and fungi from developing; however, reports on their efficacy have caused

serious concern regarding the safety of these compounds for the consumer (Anand & Sati, 2013; Bento de Carvalho et al., 2024). Due to their anti-microbial properties, most synthetic preservatives have been withdrawn from use as they have been proven to have potential cancer inducing properties and are therefore prohibited as food preservers, leading to the development of natural, organic preservatives for food.

3.2.2. Synthetic Preservatives

Preservative chemicals, which are artificially synthesized chemical substances, are added to food and agricultural produce in order to prevent microbial contamination and oxidation as well as to maintain product quality throughout the period of storage. The use of synthetic preservatives in cereal grain storage has become common over time due to their strong efficacy, affordability, and availability. Sodium benzoate, calcium propionate, sorbic acid, butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), and sulphites are examples of synthetic preservatives used for preventing microorganisms like *Aspergillus*, *Penicillium*, *Fusarium*, and grain insects from growing (Bullerman & Bianchini, 2009). Calcium propionate is widely used to inhibit mould in bread and cereal products, while sodium metabisulfite is used against bacteria and fungi in milled rice and maize (Bullerman & Bianchini, 2009).

Nevertheless, synthetic preservatives have increasingly raised alarm bells because of their possible health impacts, such as carcinogenicity, allergy reactions, and accumulated toxicity, with multiple research findings indicating negative impacts of synthetic preservatives such as irritation of the lungs, skin problems, and interference with gut microbiota in consumers (Anand & Sati, 2013). In response, various countries have introduced maximum allowable levels for certain preservatives, with butylated hydroxytoluene (BHT) and butylated hydroxyanisole (BHA) subject to regulatory limits and ongoing safety review in a number of jurisdictions; readers should consult current EU and FDA regulatory guidance directly for up-to-date permitted levels, as the specific limits are revised periodically. Despite these possible risks, synthetic preservatives still prevail in the global grain-storage business owing to their cost-effectiveness, longevity, and broad-spectrum action.

Nevertheless, recent literature suggests that over-reliance on synthetic preservatives may be undesirable on both toxicological and resistance grounds, which has raised a call for an integrated approach in which low doses of synthetics are used in combination with natural compounds (Feng, Yanshao, Wang, Zhang, & Wang, 2023). This would make it possible to minimize the usage of chemicals while still having the same effect. The use of synthetic preservatives is thus highly effective in the conservation of grains but raises some health and environmental concerns that need to be addressed through proper regulation and toxicity studies, and possibly by combining them with natural preservatives in grain conservation. Table 1 highlights the benefits of organic preservatives compared with synthetic preservatives.

Table 1. Comparative advantages of organic vs. synthetic preservatives.

S/N	Advantage	Organic Preservatives (Natural)	Synthetic Preservatives	References (2021-2025)
1	Biodegradability	Derived from renewable sources and decompose naturally, reducing environmental impact.	Often petroleum-based and may persist in the environment, contributing to pollution.	Dong, Xu, Zhang, Li, and Chen (2024)
2	Low Toxicity	Generally recognized as safe (GRAS); lower risk of adverse health effects such as allergies or carcinogenicity.	Some are associated with health risks, including allergies, asthma, and potential carcinogenic effects.	Anand and Sati (2013)
3	Consumer Acceptability	Perceived as safer and more natural, aligning with consumer demand for clean-label products.	Increasing consumer skepticism due to potential health concerns and desire for natural ingredients.	Chauhan and Rao (2024)
4	Antioxidant Properties	Contain natural antioxidants (e.g., vitamin C, E, polyphenols) that prevent oxidation and extend shelf life.	Synthetic antioxidants may not offer additional health benefits and can have negative perceptions.	Konfo et al. (2023)
5	Antimicrobial Activity	Exhibit antimicrobial effects through compounds like essential oils and organic acids, inhibiting spoilage organisms.	Effective, but may lead to microbial resistance and lack additional health benefits.	Feng et al. (2023)
6	Environmental Impact	Lower environmental footprint due to natural sourcing and biodegradability.	Production and degradation can contribute to pollution and carbon emissions.	Dong et al. (2024)
7	Flavour Enhancement	Can enhance the flavour profile of foods (e.g., herbs and spices) while providing preservative effects.	May not contribute positively to flavour and can sometimes impart undesirable tastes.	Konfo et al. (2023)

Taken together, the studies summarized above point to a consistent pattern rather than a simple binary choice: organic preservatives offer clear safety, biodegradability, and consumer-acceptability advantages, but synthetic preservatives currently retain the edge on cost, shelf-stability, and ease of large-scale application. The literature does not yet adequately explain why efficacy varies so widely between essential oils and grain types (e.g., lipid-rich grains such as groundnut and millet versus starch-dominant grains such as maize) a gap that limits practical recommendations and is addressed further in Sections 3.8–3.14 below.

3.3. Challenges in Grain Storage

The constraint of grain storage is primarily associated with the handling and movement of grains, the particular items used for the storage of grains are bags of jute and HDPE of 100kg capacity ([Adeleke, Ogunlela, Olufajo, & Iwuafor, 2013](#)) the on-farm storage of grains is mostly used through cover and plinth (CAP) storage rather than heap storage which was used previously for grains. The practice of storage of grain like wheat and paddy by the farmers in the CAP storage has been largely explored ([Omobowale, Armstrong, Mijinyawa, Igbeka, & Maghirang, 2016](#)). The steps involved in the CAP storage include making a plinth at least 0.6m (2ft) above the ground over which 50kg or 100kg bag of food grains were stacked in the form of a dome and covered from the top as well as sides with a 250-micron LDPE sheet for maize, wheat, paddy, and sorghum grains in the duration of 3-6 months. The CAP grain storage can be made within less than 3 weeks time and is found to be cost-effective. Generally, maize, paddy, sorghum, and wheat grains are stored in the form of pods in the CAP for a period of 3-6

months in Nigeria, who store between 65-70% of their rice and wheat grains for human consumption, feed, or seed and dispose of the remaining stocks through Krishi Mandis or government/private buyers.

3.4. Postharvest Spoilage of Cereal Grains

The major postharvest losses of grain attributed to farmers include weather (40%), field damage (33%), and pests during storage (16%). These are the top three factors leading to poor harvests and exacerbating food losses. Survey findings, on the other hand, have revealed that poor postharvest practices on the part of farmers are mostly to blame for food losses (Abass et al., 2014). The need for technical knowledge of farming practices in relation to climate variability would help minimize postharvest losses. Training in postharvest practices would be necessary to minimize food losses and increase household food security. According to Jain, Sivadasan, Murty, and Rai (2000) the major physiological, physical, and environmental factors resulting in postharvest losses include high crop perishability, mechanical damage, excessive exposure to high temperatures, humidity, and rain, contamination due to fungal and bacterial spoilage, attack by birds, rodents, insects, and other pests, and poor handling, storage, and processing practices. Mycotoxin contamination is no longer confined to rural areas. According to López-Castillo, Flores-Rivera, Winkler, and García-Lara (2018) mycotoxins are toxic substances produced by certain fungal species that contaminate grain. There are five major types of mycotoxins found in grains: aflatoxin, fumonisin, deoxynivalenol (DON), ochratoxin (OT), and zearalenone (ZEN). Their occurrence may begin in the field during harvesting, handling, storage, and processing.

In order to prevent spoilage, it is necessary to ensure proper aeration of the grain (Magan & Aldred, 2007) which can be done through the installation of horizontal fans in bins and silos; through proper control of airflow and fan use, the best results in preventing spoilage can be achieved for aerated wheat kept in round bins and large horizontal storage in tropical and subtropical climates. Ozone, a powerful oxidizer, is also used to enhance food quality and regarded as a cost-efficient and environmentally friendly processing method; the effect of the ozonation process on the composition (mycotoxins, for example) and physico-chemical properties (starch, protein, for example) of wheat, rice, and maize was examined by Zhu (2018) who found that ozone influences rheological properties, color, storage properties, and germination of grains. In addition to spoilage, moisture content and broken kernels of postharvest grain influence the initial bulk density of the grain and the compaction of grain under overburden; bulk density is inversely influenced by grain moisture, while packing is positively influenced by grain moisture, and the interaction between broken-grain particle size and concentration affects storage volume (Ruiz, Couto, & Aguado, 2012).

Similarly, the effects of temperature, relative humidity, and moisture content on the germination percentage of grains stored in various storage facilities are important (McNeill, Thompson, & Montross, 2004). In grain storage facilities, grain moisture content and temperature tend to rise relative to the surrounding atmosphere, and the germination percentage declines despite increases in relative humidity, primarily due to poor aeration.

3.4.1. Postharvest Losses due to Pests

The increase in pest resistance during grain storage has led to the study of peroxidases as a trait for maize breeding for the production of pest-resistant maize (López-Castillo, Silva-Fernández, et al., 2018). Antibiosis, antixenosis and preference have been established as the principal mechanisms of resistance of maize grains against *S. zeamais*. Neme and Mohammed (2017) established that crude fibre, phenolic acids, and trypsin inhibitors in whole-grain maize are sources of resistance, with higher concentrations of these biochemicals corresponding to lower infestation levels. However, existing knowledge of natural resistance to pests is still incomplete, especially knowledge about the specific participation of certain biochemical factors, such as peroxidases and phenolic acid

amides, so more research is needed to make future breeding programmes and prevent insect losses after harvest possible, thus improving food security in at-risk countries.

3.4.2. Efficiency of Components of Storage

Low aeration rates and lack of fan control were noted in all the grain storage systems studied, with limited or no control of the moisture content of the grain, temperature of the environment, and relative humidity. There is therefore a need for increased measures to reduce post-harvest grain losses. Hosakoti, Dolli, Hiremath, and Angadi (2013) suggested that appropriate sensors should be designed for monitoring the moisture content and temperature of the grain stored in the structure together with the ambient environment. The utilization of solar power for grain storage components is highly recommended where there is control of the fans using environmental parameters like a humidistat controlling a solar-powered DC fan for drying grains (Mohapatra, Kumar, Kotwaliwale, & Singh, 2017). A low-cost and energy-saving microcontroller-based humidistat has been designed to control a photovoltaic-powered DC fan, and the fan current, voltage, insulation, temperature of the environment, and relative humidity were taken at five-minute intervals to verify the expected operation. When designing storage systems, drying temperature, drying time, and the cooling system were found to be the major factors in predicting mass flow rate (Bhadra, Rosentrater, & Muthukumarappan, 2017).

3.4.3. Design and Fabrication of Components of Storage

Hermetically sealed storage vessels, such as metal silos (soldered airtight) and super grain bags (constructed out of high-density polyethylene material in order to minimize gas exchange), can be used by farmers to minimize postharvest losses. Although metal silos are highly effective, they are also costly because half of their construction cost is due to the metallic sheet, which makes the cost per kg of grain stored inversely proportional to its capacity; hence, a need for economic evaluation to determine the optimum silo volume at which it will be economically feasible, depending on prices (de Groot & Mazur, 2013). Due to the high cost and scarcity of construction materials, the appropriateness of locally available termite mound clay (TMC) to construct grain storage silo compared to reinforced concrete (RC) and galvanized steel (GS) silos has been proposed for the humid tropics (Omobowale et al., 2016). Underground pits create a moist environment for grains, resulting in infestations by insects and storage fungi; pressures in the storage vessel are more or less constant under static conditions but drop during silo discharge (Dejene, Yuen, & Sigvald, 2004).

3.4.4. System of the Silo-Hopper Storage

As mentioned in the analysis of the pressure theory of the silo and the mechanism of storage, according to Ruiz et al. (2012) in the case of the silo structure design, regardless of its dimensions, shape, and material, there are only two types of pressure that always exist. Those are the normal and vertical pressures of the grain material. Normal wall pressure exists during silo filling and emptying and is not constant in either process, requiring further study, particularly during surges in silos; it decreases after prolonged storage as frictional forces dissipate. The horizontal force of the grain material is not related to these two pressures. Maximum vertical pressure of the grain material is exerted on the silo when it is filled and can be expressed as the specific weight of the grain times the volume of the grain material in the silo per unit length times the perimeter of the silo.

3.5. Sources of Microbial Contamination of Cereal Grains

Microbial contamination of cereals takes place during their cultivation, harvesting, and after-harvest processing, such as drying and storage (Magan & Aldred, 2007) arising from a variety of sources, such as air, dust,

water, soil, insects, birds, feces of rodents, and also from equipment and improper handling. Types of microbial contamination vary depending on the geographical area where cereals are cultivated, being greatly dependent on the environment, such as drought, rainfall, temperature, sunshine, along with improper handling, harvesting, and processing equipment, and storage conditions (Bullerman & Bianchini, 2009). Rainfall prior to harvest plays an important role in the colonization of cereal ears by *Alternaria* species, causing a black fungal staining visible not only at the surface of grains but also underneath the pericarp. Sources of microbial contamination of cereals are given in Table 2, mycotoxins in cereals in Table 3, and methods of preserving cereals in Table 4.

Table 2. Sources of microbial contamination of cereal grains.

Type of Microorganisms	Name of Microorganisms	References
Bacteria	<i>Salmonella</i> , <i>Escherichia coli</i> , <i>Bacillus cereus</i> , <i>Erwinia herbicola</i> , <i>Xanthomonas campestris</i> , <i>Azotobacter</i> , <i>Pseudomonas</i> , <i>Micrococcus</i> , <i>Lactobacillus</i>	Laca, Mousia, Díaz, Webb, and Pandiella (2006) and Harris, Shebuski, Danyluk, Palumbo, and Beuchat (2013)
Filamentous fungi and yeasts	<i>Eurotium</i> , <i>Aspergillus</i> , <i>Penicillium</i> , <i>Rhizopus</i> , <i>Mucor</i> , <i>Alternaria</i> , <i>Cladosporium</i> , <i>Fusarium</i> , <i>Helminthosporium</i> , <i>Sporobolomyces</i> , <i>Rhodotorula</i> , <i>Hansenula</i> , <i>Torulopsis</i> , <i>Candida</i> , and <i>Saccharomyces</i>	Harris et al. (2013); Pitt and Hocking (2009) and Bullerman and Bianchini (2009)

Table 3. Mycotoxins in cereal grains.

Mycotoxin	Fungal Source(s)	Effects of Ingestion for Humans	Commodity
Deoxynivalenol/Nivalenol	<i>Fusarium graminearum</i> , <i>Fusarium crookwellense</i> , <i>Fusarium culmorum</i>	Human toxicoses e.g. nausea, vomiting, diarrhoea, headache, fever	Wheat, maize, barley
Zearalenone	<i>Fusarium graminearum</i> , <i>Fusarium crookwellense</i> , <i>Fusarium culmorum</i>	Identified by the International Agency for Research on Cancer (1993) as a possible human carcinogen	Maize, wheat
Ochratoxin A	<i>Aspergillus ochraceus</i> , <i>Penicillium verrucosum</i>	Suspected by IARC as human carcinogen	Barley, wheat, and many other commodities
Fumonisin B1	<i>Fusarium moniliforme</i> plus several less common species	Suspected by IARC as a human carcinogen	Maize

Table 4. Current methods and technologies used for cereal grains preservation.

Method/Technology	Description	Limitations	References
Pesticides	Chemicals designed to prevent and control the occurrence of pests causing harm to crops - moulds (Fungicides), weeds (Herbicides), and insects (Insecticides)	High environmental impacts; direct negative impact on human health; increasing resistance against pesticides	Liu, Pan, and Li (2015) and Jess et al. (2014)
Drying	Grains are dried to a low moisture content.	Lack of uniformity of the process; over-drying may damage the grains and cause economic losses, as well as increase mycotoxin contamination	Varga, Kocsubé, Péteri, Vágvölgyi, and Tóth (2010) and Magan and Aldred (2007)
Debranning	Process during which the bran layers are removed	Not completely suitable for wheat due to the crease on	Laca et al. (2006)

	from the endosperm by friction and abrasion	wheat kernels; whole-grain demand in the market	
Chlorine and hypochlorite	Due to their oxidizing capacity, chlorine and hypochlorite treatments are among the most widely used processes for microbial control	Low inactivation of fungal spores on cereal grains and generation of toxic by-products after treatment	Delaquis and Bach (2012); Virto, Mañas, Álvarez, Condon, and Raso (2005) and Andrews, Pardoel, Harun, and Treloar (1997)
Irradiation	Exposing food to a certain amount of ionizing radiation	Can negatively modify the quality and technological properties of cereals and cereal products	Lung et al. (2015) and Farkas, Ehlermann, and Mohácsi-Farkas (2014)

3.6. Grain Storage

Conservation of biodiversity in relation to the storage of grains is important now, owing to cultural heritage as well as the health of the state. Traditional grain stores should be reviewed with respect to biodiversity and associated knowledge, as pre-storage losses during drying and cleaning have been noted to be higher than losses due to storage alone. The average annual cost of storage per quintal is highest in gunny bags coated with a polythene sheet and lowest in underground storage. Implements used in post-harvest activities also cause grain loss; hence, cereals are usually mechanically threshed, while pulses are manually threshed. Grain loss during transport has been noted in tractors as well as bullock carts, and additional grain losses occur through sieving after threshing (Nwosu, 2016). Grain loss due to these factors is similar to the loss of grain due to insects, rodents, and microorganisms in storage; currently, up to 30 percent of grain is lost to natural contamination (Nwosu, 2016). Bio-insecticides have proved to be ineffective due to the biodiversity of the pest and microorganisms. During prehistoric times, rodent attacks were viewed as the sole cause of storage losses, which is very wrong because other external factors, such as humidity, moisture, and a biothermal environment, support the growth of pests and microbes. Conditions in the atmosphere prior to and during storage play an important role in determining the magnitude of losses that may accrue from grain discoloration, loss of odor, loss of the ability to germinate, and loss of nutritive and therapeutic qualities, which may not be easily noticed. Common crops stored in Nigeria include maize, wheat, barley, paddy, millet, sesame, soybean, groundnut, sorghum, and beans, in polythene bags, fertilizer bags, gunny bags, jute bags, heaps in rooms, metal bins, and underground storage.

3.6.1. Materials and Methods for Grain Storage

When grains are kept in an oxygen-free environment, the metabolism of pests and insects is affected, as seen in hermetic storage (Bhardwaj, 2015). During hermetic storage, carbon dioxide gets built up while oxygen gets reduced through respiration by the grain itself or other abiotic or biotic agents, resulting in oxygen deficiency, with carbon dioxide and oxygen buffer allowing for continuous respiration of the grain. There are methods of open-sun drying and shade drying commonly used by farmers in Nigeria that reduce the water activity of grains and harden the kernels. The general process in grain storage in Nigeria includes threshing, winnowing, cleaning, drying, bagging, ponding, dehushing, and decortication. The purpose and objectives of grain storage structures all over the world (Bhardwaj, 2015) depend on the amount of grain, its intended use (commercial, domestic, or seed), the period of storage, the place of storage, the treatment (for example, fumigation or disinfection), the number of iterations or treatments, the control procedures, and preparedness factors including dampness, humidity, temperature, and quality of grain.

3.7. Studies on the Use of Organic Preservatives

In recent years, significant progress has been made in exploring and applying organic preservatives in food systems, particularly in the preservation of cereals and grains.

3.7.1. Studies on Essential Oils as Functional Food Preservatives

A detailed review on the use of essential oils (EOs) as functional preservatives in foods was carried out by Singh, Tiwari, and Dubey (2021) covering the antibacterial, antifungal, and antioxidant properties of a number of EOs like cloves, oregano, thyme, and cinnamon, along with their efficacy in inhibiting various pathogenic bacteria and fungi found in foods. Nevertheless, some problems like volatility, pungent smell, poor aqueous solubility, and non-uniform antimicrobial activity against food pathogens have been reported. In order to address these issues, Singh suggested the use of advanced delivery systems like microencapsulation and nano-formulations. Despite having great potential, essential oils still need to be optimized using formulation science, particularly for grain-based foods.

3.7.2. Studies on Nanoencapsulation of Essential Oils in Cereal Grains

Nano encapsulated essential oils in the specific context of their post-harvest storage in cereals were emphasized by Maurya et al. (2024). The key issue of Maurya et al. was encapsulation of essential oils in biopolymeric carriers such as chitosan, alginate, and cyclodextrins due to poor stability and volatility of non-encapsulated essential oils. Indeed, nano encapsulation provided the prolonged antimicrobial effect and decreased active ingredients losses; but the authors also raised the issues of expensive production, ambiguity about food grade nanoparticles regulations, and changes of sensory quality and germination capacity of grains. Regardless of the problems mentioned above, nano encapsulation was shown to increase the shelf-life and safety of stored grains due to stable and prolonged release of active ingredients, and the authors suggested performing the pilot tests and safety evaluations of nanoparticle standards in the field of food science.

3.7.3. Studies on the Antioxidant Role of Essential Oils

A recent review article featured in Food Chemistry Advances (Konfo et al., 2023) enhanced knowledge about the potential role of essential oils as antioxidants in food systems. It dealt with aspects such as the chemical composition of EOs, methods of extraction, and the mechanisms by which EOs interfere with free radicals' chain reactions and lipid oxidation, which is a primary factor leading to spoilage of stored cereals. As noted in the paper, essential oils like thyme oil and clove oil can be used both as an antimicrobial agent and as an antioxidant, but the thermal decomposition during extraction and their reaction with foods might affect the efficacy. The use of pure and mixed essential oils proved to be more stable and efficient as antioxidants.

3.7.4. Studies on Essential Oils in Active Packaging

Tsitlakidou, Tasopoulos, Chatzopoulou, and Mourtzinos (2023) conducted a study on the incorporation of essential oils into active food packaging systems, which involved edible films and coatings that were loaded with EOs, especially EOs that were incorporated in chitosan, whey protein, and biodegradable polymers to evaluate the ability of such films to sustain a controlled release of EOs and increase the shelf-life of grains and cereals. One of the main problems that arose in the course of the study was how to ensure even dispersion of EOs in the films without weakening the mechanical resistance of the films and posing safety risks for consumers; however, the EO-laden coatings proved themselves to have excellent antimicrobial properties and the ability to maintain the food quality in different storage conditions.

3.7.5. Studies on Molecular Mechanisms and Safety Profile

According to Pisoschi, Pop, Cimpeanu, Predoi, and Ghinea (2023) the molecular mechanisms and safety characteristics of essential oils were analyzed to identify how elements such as carvacrol, eugenol, and cinnamaldehyde affect the microbial world through membrane damage, cell content leakage, and oxidative stress induction. The review indicated that efficacy has been extensively documented in both in vitro and in vivo experiments, and the study pointed out issues related to the allergic reaction, dosing, and variations in the composition of EOs caused by different plants used for production, but emphasized advancements in the field of computational biology that allows predicting the effects and toxicity of EOs. The findings of the review proved the ability of essential oils to be alternative solutions to artificial preservatives if safety evaluations are conducted in detail and suggested international regulation of essential oil use, EO chemotypes' standardization, and the combination of EOs in risk models in food safety. Together, these studies reveal a coherent trend toward safe, effective, and environmentally sustainable organic preservatives, moving from the early exploration of functional essential oils to nanoencapsulation breakthroughs, active packaging applications, and increasingly sophisticated safety and molecular analysis, underscoring that organic preservatives are no longer a niche concept but a mainstream research and development priority.

3.8. Bio efficiency of Organic Preservatives in Protecting Stored Cereal Grains

The cereal grains such as wheat, corn, rice, barley, sorghum, millet, and oats are a basis of global food security, providing a considerable portion of calories consumed per day in many parts of the world. Nevertheless, post-harvesting, cereals encounter various hazards, among which are microbiological spoilage, mycotoxin formation, insect damage, oxidation rancidity, and nutrient degradation. Cereal grain post-harvest losses may amount to 10-30% in developing countries, accounting to billions of economic losses and affecting food security (Yu, 2025). Thus, efficient methods of preservation are not only required for ensuring food safety and quality but also for supporting the livelihoods of farmers. Preservation methods such as drying, hermetic packaging, and the use of synthetic chemical preservatives have been critical in minimizing losses. However, the excessive use of synthetic preservatives like propionates, benzoates, and sorbates poses health and environmental threats, and some studies have established links between chronic exposure to these chemicals and various issues including allergies, carcinogenesis, alteration of the gut microbiome, and toxicity to the environment (Feng et al., 2023). There is also increased resistance by spoiling bacteria to specific synthetic fungicides and bactericides.

The quest for safer, environmentally friendly, and consumer acceptable alternatives has increased interest in organic preservatives, which are natural products extracted from plants, microbes, or animals, biodegradable, generally regarded as safe (GRAS), and have the capability of preserving stored grains without causing any environmental pollution. EO's and organic acids have turned out to be very promising, considering that naturalness, multi-site antimicrobial action, and suitability with the current trend of clean label foods make them attractive both to consumers and to regulatory agencies (Iwayemi, Yu, Rehrah, Davis, & Williams, 2024). "Bio efficacy" is used here to denote the ability of these natural substances to inhibit or suppress spoilage organisms, retard chemical decomposition, and preserve sensory and nutritive properties of the grains for a longer period of storage; bio efficacy of the organic preservatives depends upon their chemical nature, storage stability, mode of application, and their interaction with grain substrates. Modern studies are exploring new methods of formulation, including nanoencapsulation, emulsification, and active packaging (Maurya et al., 2024).

3.8.1. Antimicrobial and Antifungal Action

Another major way that natural preservatives help preserve stored cereals involves the process of antimicrobial action. Essential oils like thyme, cloves, oregano, cinnamon, and carnation have high levels of phenolics, terpenoids, and aldehydes, including thymol, carvacrol, eugenol, and cinnamaldehyde that affect the structure of microbial cell membranes by causing leakage of intracellular content, loss of membrane potential, and disruption of biochemical reactions (Feng et al., 2023). Thymol and carvacrol, found in thyme and oregano oils, respectively, disrupt the structure of lipid bilayers of the hyphae of fungi and cause their death; when used in vapor form, both oils have shown a significant inhibiting effect on the growth of *Aspergillus flavus*, *Fusarium graminearum*, and *Penicillium verrucosum*, three fungi that can seriously damage cereals (Yu, 2025). The effectiveness of clove oil, abundant with eugenol, is similar as no microbial regrowth occurred.

This antimicrobial action is not limited to fungi; several bacterial contaminants of stored grains, including *Bacillus cereus* and *Salmonella enterica*, show marked susceptibility to EO vapors and surface treatments. Iwayemi et al. (2024) found that application of cinnamon oil at 0.5% concentration reduced bacterial counts on wheat kernels by more than 4 log units within 48 hours. The multi-target nature of EO activity is a key advantage over synthetic preservatives, which often act through single biochemical pathways, and this multi-target activity reduces the likelihood of microbial resistance, a critical consideration for long-term sustainability.

3.8.2. Mycotoxin Suppression

In addition to inhibiting fungal growth, specific natural preservatives help suppress mycotoxin production, another health hazard associated with storing cereals. Mycotoxins such as aflatoxin B1 (AFB1) produced by *A. flavus* and ochratoxin A (OTA) produced by *A. ochraceus* are extremely toxic, carcinogenic, and not easily degradable during food processing. EOs suppress mycotoxins either through inhibition of fungus growth responsible for the formation of toxins or interference with the secondary metabolic pathways of the fungi; lab experiments reveal that thymol, eugenol, and cinnamaldehyde could suppress the activity of genes responsible for the production of aflatoxin by suppressing the biosynthesis process even in the presence of active growth of the fungus (Yu, 2025). The 2024 pre-storage wheat experiment using 1% thyme oil, 1% carnation oil, and 1% malic acid resulted in full suppression of fungus growth in 14 days, while increased concentrations to 8% suppressed AFB1 and AFB2 from 12 ng/g concentration in unprocessed samples to an undetectable level (Abdel-Kader, Ibrahim, Khalil, El-Mougy, & El-Gamal, 2025). It means that EOs not only inhibit fungal growth but also reduce toxin production, providing an additional layer of safety compared with synthetic preservatives, which may suppress fungi but not toxins.

3.8.3. Antioxidant and Insect-Repellent Properties

In addition, the oxidative stability of stored grain is an equally important shelf-life parameter. Fats found in cereals such as corn and oats cause rancidity due to oxidation of fats, causing off-flavors, loss of nutrients, and marketability. Essential oils such as rosemary, thyme, and oregano are known for containing natural antioxidants like rosmarinic acid, thymol, and carvacrol, which scavenge free radicals, chelate pro-oxidative elements, and inhibit the propagation phase of lipid oxidation (Maurya et al., 2024). Pests like *Sitophilus zeamais* and *Tribolium castaneum* are responsible for post-harvest loss of crops, and many EOs serve as insect repellents, prevent oviposition of eggs, and work as fumigation agents; as seen by Yu (2025) in a study of corn stored under hermetically sealed conditions, where 0.5% concentration of clove oil vapor significantly decreased the rate of infestation of maize weevils by over 70%. The synergism of antimicrobial, antioxidative, and insect repellent properties in one single preservative makes the overall efficacy of the bio-agent more effective.

3.9. Recent Technological Innovations

3.9.1. Nanoencapsulation of Essential Oils

Among the innovative ways in which organic preservatives have been used to preserve cereals in storage is nanoencapsulation, which involves trapping the essential oils into nanosized carriers composed of biodegradable food-grade polymers such as chitosan, alginate, or cyclodextrins. The approach helps address the fundamental problems that come with the use of essential oils as preservatives in food products due to volatility, oxidation, and instability, among other factors. Encapsulating essential oils in biodegradable, food-grade polymers protects the compounds within the oils from degradation by external factors, such as light, heat, and oxygen, thereby increasing their shelf life (Maurya et al., 2024). Nanoencapsulation ensures controlled release of the essential oils, which ensures that there is consistency in the antimicrobial concentration in the storage of grains in situations where one application must work for several months. The kinetics of release can be modified through alteration of carrier composition, particle size, and charge; lower particle sizes increase the surface area, thus increasing the antimicrobial contact. Chitosan carriers provide an additional antimicrobial property.

The study on Maurya et al. (2024) found out that nano-encapsulated thyme oil retained more than 80 percent of its antifungal efficacy for a period of six months, compared to less than 30 percent of the free (unencapsulated) oil, while, in the maize storage experiments, nano-encapsulated clove oil was able to reduce the number of *A. flavus* colony-forming units by more than four log cycles within 90 days without compromising its sensory characteristics. Nanocapsulation technology presents an opportunity to combine EOs with the active packaging materials through the incorporation of the nanocapsules in polymer films or coatings applied on bags or silos storing grains without allowing contact between the oil and the grain (thus, without altering the sensory attributes) but releasing its volatiles continuously to protect the grains from any microbial or insect attack. However, scalability and cost remain issues due to the need for specialized equipment for nanocapsulation technology (Yu, 2025).

3.9.2. Rational Blend Formulations

Other advances improving bioefficiency include the formulation of rational blends of two or more essential oils or essential oils mixed with organic acids to make use of the synergy between antimicrobial actions. The logic behind this approach is that different bioactive components work on different metabolic routes of microorganisms and thus when applied together, they provide a more effective and wider antimicrobial protection effect even at low concentrations. It has been found that the blend of thyme oil (thymol) and carnation oil (eugenol) inhibits a wider spectrum of storage fungi than each oil separately (Abdel-Kader et al., 2025) and thus low doses can be used without sensory effect. The addition of organic acids (malic acid, potassium sorbate) provides an additional antimicrobial effect through pH reduction and creation of an unfavorable environment for microbes.

In a study on wheat preservation using a combination of 1% thyme oil and 1% carnation oil, the results showed that no fungal infection occurred for 60 days at 1% each, while at 2% each, there was no infection (Iwayemi et al., 2024). In addition, the inclusion of 0.5% malic acid to a thyme and carnation blend not only inhibited *A. flavus* development but also lowered the aflatoxin levels to more than 95%. It is essential to have a proper formulation of the EOs because some chemicals within these EOs might react with each other to lower their effectiveness and, hence, require a compatibility test to be done on them, which will be facilitated through the use of gas chromatography-mass spectrometry (GC-MS) profiling of volatile composition before and after blending. Commercially, a rational blend can save cost in that one can substitute costly EOs with less expensive but equally effective ones.

3.9.3. Practical Case Studies and Efficacy Data

The bioefficiency of organic preservatives needs to be examined by properly documented field and laboratory tests. According to Yu (2025) there was an extensive study that involved the use of clove oil, thyme oil, and cinnamon oil in stored wheat in controlled environmental settings; wheat grain infected with *A. flavus* was subjected to 1%, 4%, and 8% EO solutions and stored at 25 degrees centigrade and 70% relative humidity for 60 days. The 8% treatment inhibited all fungal growth and decreased aflatoxin B1 concentration to below 0.5 ng/g detection limit.

However, another study Iwayemi et al. (2024) evaluated the effectiveness of six EOs (cinnamon, clove, eugenol, orange terpenes, oregano, and thyme) in their vapour phase against naturally contaminated maize; after 30 days of hermetic storage, cinnamon and clove oils resulted in over 90% reduction in the number of fungal colonies, while oregano and thyme oils provided between 75-85% reduction. Pre-storage wheat trials illustrated the effectiveness of EOs when combined with organic acids (Abdel-Kader et al., 2025): a 1% concentration of thyme oil along with 1% malic acid eliminated all detectable *A. flavus* within 14 days, whereas the pure EO required 28 days to achieve complete inhibition, and also preserved sensory qualities better than high concentrations of individual EOs — an evident benefit for consumer acceptance. Regarding pest control, Yu (2025) evaluated the vapours of clove oil on hermetically stored maize infested with *Sitophilus zeamais*; at a 0.5% concentration, clove oil reduced the number of emerging insects by 72%, while a 1% concentration inhibited emergence by more than 90% without the use of chemical insecticides. All case studies described above exemplify the ability of organic preservatives to provide consistent and multifaceted protection both in laboratory and real storage conditions.

3.10. Limitations, Challenges, and Future Directions

However, despite the enormous promise they hold, the broad usage of natural preservatives, especially essential oils (EOs), is inhibited by several issues. The variation in the composition of EOs based on the plant species, cultivars, geographical location, harvest time, and extraction process poses difficulties in standardization and regulatory compliance (Feng et al., 2023). The aromatic nature of these compounds could also adversely impact the sensory properties of stored grains. However, such impacts can be minimized through encapsulation and rational blending of EO formulations. High cost of production and processing, as well as a lack of nanoencapsulation facilities, pose major constraints, especially in developing nations. In addition, regulatory requirements differ from one region to another regarding permitted dosages, residues, labeling, and additional safety evaluations for nanoformulations (Yu, 2025). Limited knowledge among farmers and grain handlers about proper application also limits efficacy. Future research should, therefore, center on the standardization of EO formulations through chemotyping and analytical methods such as GC-MS and HPLC, conducting extensive field trials across varied agroecological zones, investigating the long-term impacts on the quality and sensory characteristics of grains, and reducing costs by using local raw materials.

3.11. Nanoencapsulation Process and Its Advantages for Stored Cereal Grains

Cereal grains like maize, wheat, rice, sorghum, and millet form the backbone of food security around the world; nevertheless, after harvesting, they suffer from multiple threats during storage in terms of contamination by fungi, mycotoxin formation, insect infestation, and oxidative damage. Loss during storage is even more prevalent in tropical and sub-tropical regions, where losses amount to over 20% of total yield (Weisany et al., 2022). The use of traditional chemicals such as propionates and sorbates is effective, but the call for safer, eco-friendly, clean-label products has gained momentum in recent years. Essential oils from plant sources like thyme, oregano, clove, garlic, and cinnamon serve as powerful natural preservatives owing to their broad spectrum antimicrobial, antifungal, and

antioxidative properties; however, the application of EOs for storage has some limitations including volatilization, photo-oxidation, instability in aqueous solutions, and their pungent smell that affects grain quality attributes (Maurya, Prasad, Das, & Dwivedy, 2021) thus making them less efficient during long-term storage. The nano-encapsulation technique provides an ideal solution to address these limitations by using nanocarriers of biocompatible and biodegradable substances, thereby increasing their stability, regulating their release rate, and enhancing the bioefficacy of EOs during grain storage (Rehman Sheikh, Wu-Chen, Matloob, Mahmood, & Javed, 2024).

3.12. Nanoencapsulation Process

The method of nanoencapsulation involves the encapsulation of active substances into carriers at the nanometre level (1-1000nm). This results in the formation of nanoparticles, which shield the inner core and provide for its controlled release. Within the scope of grain preservation, the inner core usually comprises the essential oil, whereas the outer shell comprises biopolymers of food-grade origin, including chitosan, alginate, starch, or proteins. The procedure includes the following stages (Figure 1):

3.12.1. Preparation of the Oil Phase

The essential oil is dispersed in an appropriate solvent or emulsified with surfactants to create a stable oil-in-water mixture.

3.12.2. Formation of Nanoparticles

Several methods are available for forming nanoparticles, described below.

3.12.3. Ionic Gelation

Positively charged polymers (e.g., chitosan) interact with negatively charged cross-linkers (e.g., sodium tripolyphosphate) to form nanoparticles.

3.12.4. Nano Emulsion Techniques

High-energy methods (ultrasonication, high-pressure homogenization) or low-energy methods (phase inversion) are used to produce fine oil droplets stabilized by emulsifiers.

3.12.5. Coacervation

Phase separation of a polymer solution leads to encapsulation of essential oil droplets within polymer-rich coacervate droplets.

3.12.6. Drying and Stabilization

Nanoparticles are dried through spray drying, freeze drying, or vacuum drying to produce a stable powder that can be stored or used in grain packaging materials.

The analysis of nano-encapsulated essential oils (EO-NC) is vital for ensuring high quality of the end product, since particle size and polydispersity index (PDI) are determined using dynamic light scattering for uniformity, zeta potential determines the surface charge, and encapsulation efficiency (EE) is calculated as the percentage of essential oil entrapped inside the nanoparticle. Encapsulation efficiencies above 80%, with particle sizes in the sub-micron range, have been reported for garlic essential oil encapsulated in chitosan nanoparticles (Li, Qiao, & Zhang, 2025).

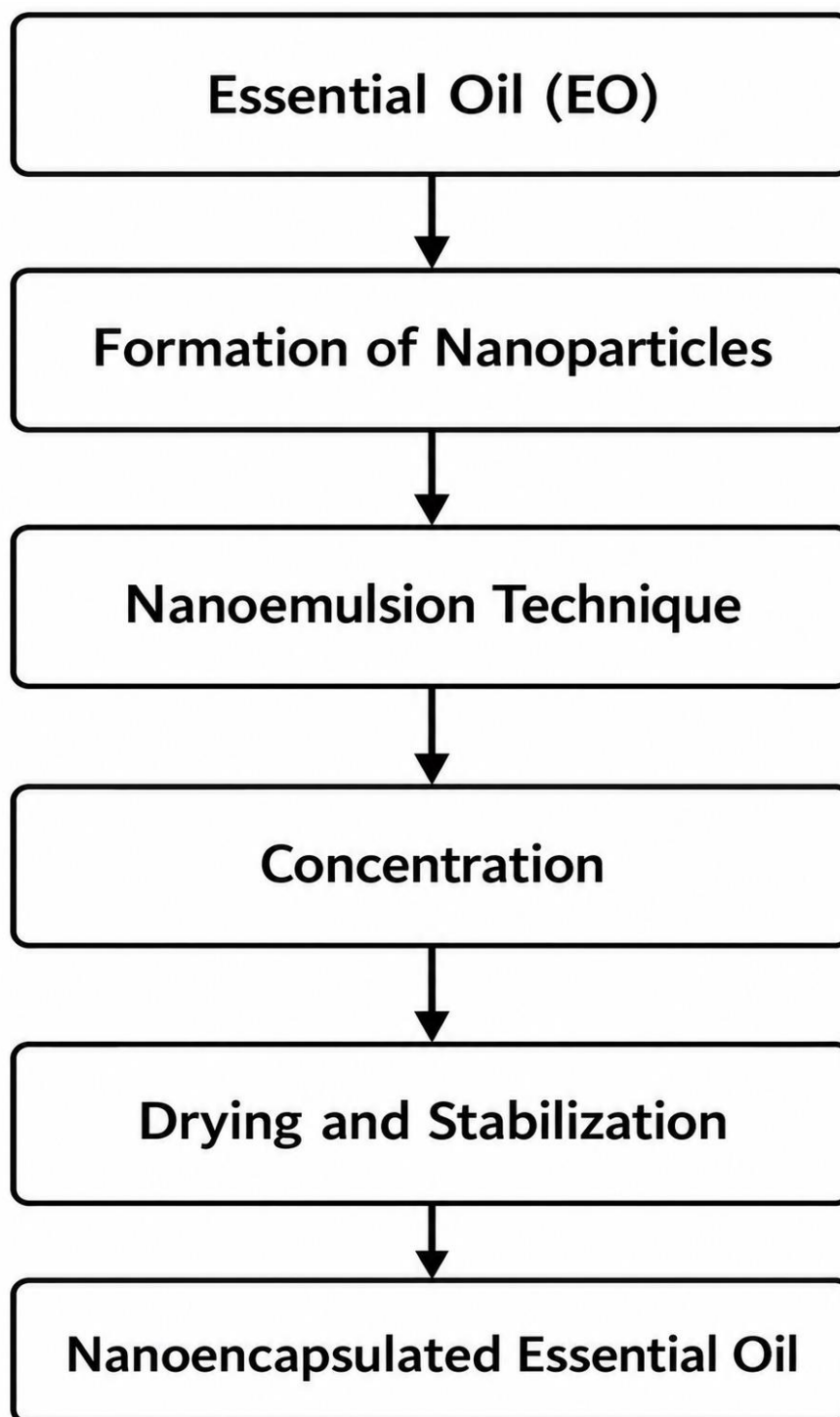


Figure 1. Flow chart illustrating the preparation of nanoencapsulated essential oil (EO) through nanoparticle formation using the nanoemulsion technique, followed by concentration, drying, and stabilization to obtain the final nanoencapsulated product.

Source: Li et al. (2025).

3.13. Advantages of Nanoencapsulation for Stored Cereal Grains

3.13.1. Enhanced Antimicrobial and Antifungal Efficacy

Through nanocapsulation, the dispersibility of hydrophobic essential oils in the grain storage environment is improved, thereby enhancing their interaction with fungal spores and bacteria on the grain. The small size of the nanoparticles makes it easier for them to penetrate into the microbial biofilm, causing damage to cell membranes and blocking metabolism, unlike when using free EO (Maurya et al., 2021). During the wheat storage experiment,

nano-encapsulated oregano oil was able to reduce *A. flavus* colony-forming units by over 90 percent within 90 days compared to free oregano oil that reduced it by 65 percent within the same period (Weisany et al., 2022).

3.13.2. Mycotoxin Suppression

Aflatoxin B1 and ochratoxin A are significant food safety threats in stored grain products. Nano-encapsulated EOs not only help prevent the growth of the fungi that produce these mycotoxins, but they also disrupt the biosynthesis of the toxins; nanoparticles of garlic essential oil have been reported to inhibit aflatoxin production in maize grain samples stored under warm, humid conditions over several weeks (Li et al., 2025).

3.13.3. Controlled and Sustained Release

One of the biggest benefits of using nanoencapsulation technology is controlled release. Instead of releasing the essential oils in one instant, when the effects are not going to last long, the release takes place gradually for weeks and even months, keeping the concentration level necessary for antimicrobial properties (Rehman Sheikh et al., 2024). It is especially beneficial in hermetic storage systems because of vapor release.

3.13.4. Improved Stability and Shelf Life

Essential oils are very susceptible to oxidation and evaporation due to exposure to air, heat, and light. The encapsulation technique helps protect them against such influences, which preserves their biological effectiveness and structure; according to Maurya et al. (2021) after six months, encapsulated clove essential oil maintained more than 80% of its antioxidant activity, whereas free EO lost about 40%.

3.13.5. Reduced Sensory Impact

Free essential oils in high concentrations may give stored grains a strong aroma and flavor that consumers may not like. With nanoencapsulation, the essential oil is only released when it is needed, thus masking the taste and smell of the essential oil and preventing strong smells from bursting suddenly (Li et al., 2025).

3.13.6. Uniform Coverage and Application Flexibility

Nano-encapsulated essential oils can be applied as powders or coatings or integrated into active packaging materials, enabling more uniform distribution over grain surfaces than bulk essential oil application. This ensures consistent protection and reduces untreated pockets where spoilage could occur (Weisany et al., 2022). Nanoencapsulation, therefore, represents a transformative advance in the application of organic preservatives for stored cereal grains: by addressing the limitations of free essential oils, namely volatility, instability, poor solubility, and sensory intensity, it enhances antimicrobial potency, prolongs release, protects against environmental degradation, and maintains consumer acceptability. While further research is needed to optimize formulations for cost-effectiveness and scalability in low-resource settings, current evidence strongly supports integrating nanoencapsulation into modern grain storage systems.

3.14. Key Challenges in Applying Nano-encapsulated Organic Preservatives

3.14.1. High Cost and Limited Scalability

Nanoencapsulation technologies, while promising for preserving the activity of organic compounds, often carry significant financial implications. Materials used in producing nano-encapsulated carriers, such as chitosan, alginate, or liposomes, are relatively expensive compared to conventional food preservatives. Because many of these materials must meet strict food-grade purity standards, their market price increases further. Equipment needed to

produce nano-sized particles, such as high-pressure homogenizers, ultrasonication devices, or spray dryers, requires substantial capital investment, continuous maintenance, skilled operators, and energy, all of which add to operational costs. For small and medium-scale food industries, especially in developing nations, these financial requirements create a barrier to adoption, and unlike synthetic chemical preservatives, nano-encapsulated organic alternatives are still largely seen as niche technologies used mainly in high-end or export-targeted products.

However, scaling up from the research stage in laboratories to an industrial level is faced by other challenges as some encapsulation technologies optimized in laboratories cannot be reliably applied on a large scale because of batch variations, the problem of standardization in the encapsulation process, and the lack of industrial protocols for the same; the storage or the shelf life of the encapsulated products also poses economic challenges as the degradation of products with time or during storage is a risky venture for producers when taking into consideration the price-performance ratio which is still an issue because of the existence of cheap chemical preservatives with equal performance levels. Lack of support from public-private partnerships in many parts of the world, inadequate funding, and government policies favoring chemical preservative technologies also act as major obstacles (Tajkarimi, Ibrahim, & Cliver, 2010). The pricing of the products is another challenge, as including nano-encapsulated preservatives may drive up the prices of the products; this may affect the pricing of staple products like maize, rice, or wheat, which are price sensitive (Weisany et al., 2022).

3.14.2. Stability and Controlled Release Issues

Another key advantage of nanoencapsulation is the potential to preserve compounds like essential oils, which are vulnerable to changes in the environment; nevertheless, being able to consistently preserve such compounds against degradation from the effects of the environment represents one of the biggest technical challenges associated with the implementation of this process for grain storage systems. Environmental conditions such as changes in temperature, moisture levels, contact with oxygen, and the intensity of the light can lead to degradation of the polymer or lipid used in encapsulation as well as the encapsulated core; if the encapsulating polymer or lipid becomes fragile at lower humidity levels or melts at higher temperatures, there may be early release or complete degradation of the nanoparticle (Singh et al., 2021). The period in which grains are stored can vary from a few weeks up to over a year, meaning that the preservative needs to stay active during the whole process, but some nanoencapsulation techniques find it difficult to stay effective during the process due to a lack of environmental control (Weisany et al., 2022).

Controlled release of active ingredients is an additional challenge as preservatives are expected to gradually release their components in response to certain triggering factors (for example, growth of microbes or changes in pH), or continuously in order to provide constant protection; however, most of the existing technologies either release too fast (and thus provide only temporary protection), or too slow (thus delaying the necessary antimicrobial effect). It is complicated to ensure release kinetics that fit the time period during which spoilage or infestation occurs in stored grain, and these may vary depending on the type of grain and storage conditions. Grain characteristics (roughness, humidity, and porosity) may influence the behavior of the nano-encapsulated product in terms of interactions with the surface of grains and, consequently, inactivation of release. The technological complexity grows further when talking about scaling up the production, since even a stable nano-formulation in the laboratory conditions might not demonstrate similar stability in the case of industrial processing and storage, and subsequent post-encapsulation treatments (for example, drying or milling of the product). More research is needed into smart release systems, such as stimuli-responsive nanocarriers that react only when specific microbial or environmental thresholds are met (Singh et al., 2021; Weisany et al., 2022).

3.14.3. Sensory Impact and Consumer Acceptability

Clove, thyme, and garlic essential oils are some of the well-known compounds that have a very distinctive odor and flavor, which are helpful in antimicrobial properties, but can pose a problem when considering the sensory quality of the treated grains. Nanoencapsulation masks these qualities until the moment of release, but does not remove them; once released, whether due to environmental or time-dependent factors, the release results in a very distinct smell and flavor of the grain (Maurya et al., 2024). This can prove to be an issue for staple crops like maize, rice, or wheat, which need to have no distinct smell; any unpleasant aroma, bitter taste, or even the presence of an essential oil smell can be a deterrent.

Consumer perception also acts psychologically because labeling of products as 'treated with essential oils' or 'nano encapsulated preservatives' might be a source of skepticism for consumers, who do not have knowledge about the use of nanotechnology and the consumption of essential oils, since 'nano' is stigmatized in certain markets. Inconsistent release of essential oils is another source of variation in consumer perceptions of sensory outcomes across product batches. During the processing of food, such as boiling, milling, or fermentation, the presence of residual essential oils might cause volatility and hence an unpleasant odor or taste. This will prevent consumers from adopting this technology, who are attached to their food legacy. The effects of nano-encapsulated essential oils on the long-term storage of processed foods such as flour and paste remain to be investigated. Consumer tests, flavor masking, and double-layered nanoencapsulation (where the second layer prevents the further release of the EOs) are under investigation. However, lack of sensory interference control is the major drawback (Weisany et al., 2022).

3.14.4. Interaction with Food Matrix

Nanocarriers' ability to preserve food effectively will depend not only on the effectiveness of their preparation but also on their behavior in the food medium, i.e., grain storage in this case. Grain comprises different chemical entities, including carbohydrates (mostly starch), proteins, lipids, and minerals, which can affect the behavior of nanocarriers or active ingredients both physically and chemically, impacting the rate of their release, stability, and eventually effectiveness as antimicrobials (Singh et al., 2021). Lipid-containing grains like groundnuts or millet can have a greater affinity for lipophilic essential oils than carbohydrate-containing grains like maize, thereby limiting the availability of the bioactive substance at the site of contamination or insect infestation. In contrast, in the other cases, the oil binds to grain proteins, limiting its free concentration and thus effectiveness as an antimicrobial. Moisture content will also be important, as insufficient moisture will impair the delivery of nanocarriers and essential oils, while excessive moisture will destabilize the nanostructure, leading to rapid depletion. Such complicated dynamics make it difficult to develop a universal formula.

Naturally occurring enzymes within the grain or in the storage environment can also degrade the nanocarrier; proteinases or amylases can cause decomposition of protein- or starch-based nanoparticle encapsulation, resulting in early release or spoilage of the product, depending on the application and timing of release. Other factors related to the matrix include pH and ionic strength, which vary between grains and have an effect on the stability of the nanocarrier via electrostatic forces; positively charged chitosan nanoparticles, for instance, can react poorly to negatively charged proteins found on the surface of the grain, causing agglomeration and poor dispersal. Finally, there is little research on the effects of mechanical stress caused by actions such as packaging, pouring, or milling on nano-encapsulated preservatives since mechanical force can result in premature breakdown of the nanocarrier. In light of all the above, the product development process requires tailoring to the particular grain matrix, which leads to higher costs and slower commercialization. Food matrix interaction is going to stay one of the major bottlenecks of the technology until more information about different grain matrices is available (Singh et al., 2021).

3.14.5. Regulatory and Safety Concerns

Despite the rising popularity of nanoencapsulation of food preservatives, there is still no regulation harmonization, especially regarding the storage of cereal grains. While most of the used encapsulating agents have GRAS status, there are still doubts about the metabolic pathways, bioaccumulation, and possible toxicity of nanoparticle compounds, which might cause inflammation and damage to organs (Das, Ghosh, & Mukherjee, 2021). The lack of long-term safety information on the intake of nanomaterial-treated grains and stricter evaluation procedures by regulatory agencies increase development costs and slow the commercialization process. The inconsistent regulations across countries, unclear labeling rules, and poor consumer acceptance, due to a negative attitude toward nanotechnology as an artificial and risky technology, make it difficult to apply. Also, there are no established guidelines for disposing of the used nanoencapsulated substances. Therefore, further toxicological research, regulatory harmonization, labeling standards, and public campaigns are needed for the successful implementation of nanoencapsulation in grain preservation (Das et al., 2021).

3.15. Formulation of New Organic Preservatives from Natural Compounds

In view of the increasing need for the development of methods for the preservation of food that is natural and safe, there have been studies on natural preservatives obtained from natural products. Although synthetic preservatives are effective, they have generally not received acceptance owing to possible dangers to human health, including allergic reactions and toxicity (Tajkarimi et al., 2010) consequently, the examination of natural products like D-limonene, a component of essential oils of citrus, and ethanol, an alcohol found in foods, has become necessary due to their ability to preserve foods.

3.15.1. Natural Preservatives and Their Mechanisms

The D-limonene compound is a terpene that has been proven to have antimicrobial, anti-fungal, and antioxidant characteristics. Due to its hydrophobic nature, D-limonene can interact with the membranes of microbial cells, hence causing permeability, leakage of cellular contents, and ultimately death of the microbial cells (Burt, 2004) the substance also possesses antioxidant properties by scavenging free radicals and inhibiting lipid peroxidation in foods with high-fat content (Ghorbani, Dabbagh Moghaddam, Sharifan, & Kiani, 2021). Conversely, ethanol acts mainly as an antimicrobial agent through protein denaturation, dissolution of lipids in the membrane, and interference with metabolic processes (Sweet, Kroon, & Webber, 2024) of microorganisms.

3.15.2. Synergistic Effects of Combined Preservatives

The latest research shows that the combination of natural preservatives may result in the occurrence of synergism, in which the antimicrobial or antioxidant effect of the combination exceeds the sum of the independent effects (Chorianopoulos et al., 2004). As far as the combination of D-limonene and ethanol is concerned, it increases the ability of the combination to disrupt cell membranes and intracellular fluid loss in the microbes more effectively than in case of use of each of these preservatives independently: due to the lipophilicity of D-limonene, it makes microbial membranes more penetrable, and ethanol disrupts the metabolic processes in cells, whereas D-limonene acts as an antioxidative agent and ethanol suppresses the growth of microbes.

3.15.3. Application in Food Systems

Possible uses of combinations of D-limonene and ethanol include several food systems, such as beverages, dairy products, and baked foods. In citrus-flavored drinks, for example, the combination of D-limonene and ethanol would allow enjoying the natural flavor of D-limonene and using the ability of ethanol to inhibit the growth of microbes

without affecting taste when used in acceptable amounts; on the other hand, in baked goods, the combination of D-limonene and ethanol is effective due to the volatility of ethanol that evaporates quickly during the process of baking. The formation of these combinations should be properly optimized, taking into account several parameters such as pH, water activity, temperature, and interaction with food matrix (Tajkarimi et al., 2010).

3.15.4. Safety and Regulatory Considerations

However, natural preservatives are GRAS, but the combinations should be tested for toxicity, allergenicity, and effect on sensory properties. D-limonene is known to be safe for use in foods, but high amounts can lead to off-flavors or reactions with other ingredients in foods (Burt, 2004) ethanol, although commonly used in food and beverages, requires careful regulation of concentrations in order to conform with food safety regulations. The authorities like FDA and EFSA guide permitted levels of natural preservatives, and any new formulation should meet these requirements in order to ensure the safety and acceptance of the product (Ghorbani et al., 2021). The future research on the formulation of new natural preservatives should include the optimization of synergistic combinations and elucidation of the mode of action of the preservatives in various food systems; high-throughput screening of essential oils and food-grade solvents can reveal the optimal combination, and nanotechnology can be used in the delivery and targeted release in order to increase shelf life and reduce sensory effects. Such a combination of natural preservatives will eventually replace artificial preservatives according to consumers' preferences and improve food security.

4. CONCLUSION

The review demonstrates how organic preservatives of specific essential oils, namely those containing mainly thymol, eugenol, carvacrol and cinnamaldehyde, can offer almost universal protection against fungi, insects, oxidation and pests in stored cereal grains, and how nanoencapsulation can bring significant improvement in their stability, controlled release and sensory acceptance in contrast to conventional free oils. But to realize this on a commercial scale will not be simply a matter of lab-proven efficacy; it will be about bringing together a paradigm that overcomes the high cost of oils, nanoencapsulation and small-scale storage systems in the mid-term, which is now clearly proven to be effective at lab scale, in the developing world where most postharvest losses occur. This paradigm must develop along three parallel lines – standardization of formulations via chemotyping and analytical quality control, reduction of the cost of encapsulation using locally available nano carriers, cheap inputs and simplified processes, and harmonization of standards for food-grade nanoencapsulates at international level, including supporting on-farm quality control. It is in the intertwined development of these three approaches, rather than in additional efficacy trials, that the future of organic preservatives for the grain security will be found.

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