



Organic Preservatives for Cereal Grain Storage: Mechanisms, Nanoencapsulation Advances, Challenges, and Future Prospects – A Narrative Review (2000–2025)

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ABSTRACT

Post-harvest grain spoilage caused by fungi, bacteria, insects, and oxidative rancidity remains one of the leading threats to global food security. Synthetic preservatives such as propionates, benzoates, sorbates, and sulfites have long been used to protect stored foods; however, growing evidence linking some of these compounds to carcinogenicity, allergenicity, and persistent environmental residues has stimulated interest in organic (natural) alternatives. This narrative review synthesizes literature published between 2000 and 2025 on the application of organic preservatives, principally essential oils, in cereal grain preservation, with attention to their antimicrobial, antifungal, antioxidant, and repellent properties, as well as recent advances in nanoencapsulation and formulation science. The evidence reviewed indicates that essential oils such as thyme, clove, cinnamon, and oregano oils can disrupt microbial cell membranes, suppress mycotoxin biosynthesis, and repel storage pests; for example, encapsulated thyme oil has been reported to retain over 80% of its antifungal activity after six months of storage, compared with less than 30% for the free (unencapsulated) oil, while clove oil vapour has reduced maize weevil emergence by more than 70% in some trials. Nanoencapsulation using carriers such as chitosan and alginate can enhance the stability and efficacy of these preservatives with minimal effect on grain quality. Nonetheless, high manufacturing costs, limited scalability, compositional variability, food-matrix interactions, and the absence of harmonized regulatory frameworks continue to constrain widespread adoption. This review concludes that organic preservatives, combined with encapsulation technologies, offer a promising and environmentally sustainable complement to synthetic chemical preservatives in grain storage, and that realizing this potential will require coordinated investment in cost-reduction research, standardization, and international regulatory harmonization.

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INTRODUCTION

Preservatives are chemicals, which could be artificial or organic, used in foods like cereals, fruits, vegetables, processed foods, cosmetics, and medicines to enhance the shelf life of the foods by ensuring that they are protected from microbial growth, fermentation, acidity, and decomposition (Teshome *et al.*, 2022). Various kinds of meat, including hams and fish, are preserved by salting, whereas jams and jellies are preserved in high sugar content (Sethi *et al.*, 2025). The Indians and Chinese have also used spices to preserve food and pickled vegetables in salt, vinegar, lemon, or mustard oil (Ganie *et al.*, 2022). Canning and pasteurization changed food preservation in the early 19th century, and the present-day sterilization processes include irradiation, filtration, and chemical addition (Anand & Sati, 2013; Knorr & Augustin, 2023).

Ensuring high-quality food safety has always been a major concern for humans since ancient times. Humans have always been improving their diets and hunting skills, taming animals and plants, preserving food using physical means, and manipulating molecules in food to improve taste or extend shelf life (Schreiber *et al.*, 2019). The use of food additives and technology is instrumental in ensuring the provision of

affordable, nutritious food, thereby minimizing losses, increasing the quality and shelf life of food products, and developing new formulations that meet market demands (Chauhan & Rao, 2024).

Food preservation is a very important part of the food industry since it ensures that food products are preserved safely for consumption (Ogwu & Ogunsola, 2024). The shelf life of food products has been greatly enhanced by chemical and natural (organic) preservatives developed alongside food preservation methods such as heating, cooling, salting, drying, and the use of artificial chemicals (Chauhan & Rao, 2024). Chemical preservatives have been among the oldest methods used to prevent food from spoiling by inhibiting bacteria and fungi; despite their ability to inhibit bacterial growth and extend shelf life, there has been significant concern about their safety for consumers (Anand & Sati, 2013; Bento de Carvalho *et al.*, 2024). While most synthetic preservatives have strong antimicrobial properties, their use has been banned due to potential cancer risks, prompting the search for natural or organic food preservatives.

Scope and objectives: This review is delimited to organic (natural) preservatives applied to cereal grains specifically (maize, wheat, rice, barley, sorghum, and millet), rather than

food preservation more broadly. Its specific objectives are to (i) synthesize evidence on the antimicrobial, antifungal, antioxidant, and repellent mechanisms of organic preservatives in stored cereals; (ii) evaluate recent formulation advances, particularly nanoencapsulation, that improve their efficacy and stability; and (iii) identify the technical, economic, and regulatory barriers that currently limit their large-scale adoption relative to 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 adoption.

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")), restricted to peer-reviewed, English-language publications indexed in the databases listed. 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.

RESULTS AND DISCUSSION

Discussion of Thematic Findings

Cereals

Among the world's most important agricultural products are cereals, which form the main part of people's diet and the primary source of nutrition in animal feeding operations (Pickard *et al.*, 2005). Cultivation of cereals has played an important role throughout history since the advent of agriculture and currently accounts for 60% of the world's cultivated area (McKevith, 2004; Awika, 2011; Shiferaw *et al.*, 2013). With the rise in global demand for cereals, cereal production has grown immensely over the last fifty years (Lal, 2016). The main cereal crops include corn, rice, wheat, barley, sorghum, millet, oats, and rye (FAO, 2017). Although crucial agricultural commodities, cereals can easily become contaminated by many environmental factors, including the soil, water, air, insects, rodents, birds, storage premises, and microorganisms. Fungal contamination and mycotoxin production are among the biggest food safety issues due to their negative impact on health (Bennett & Klich, 2003). Grain losses due to fungi and mycotoxins are estimated as 5–30%, with additional losses due to insects and rodents, especially in developing countries (Kumar, D., & Kalita, 2017; Mesterházy *et al.*, 2020). Thus, grain moisture between 12–13% and water activity below 0.70 are crucial for inhibiting the growth of microorganisms in grains (Rifna *et al.*, 2022; Oluwakayode *et al.*, 2024).

Organic vs Inorganic Preservatives

Organic Preservatives

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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 *et al.*, 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 (Natural) Preservatives	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 et al. (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 & 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 & 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.

Challenges in Grain Storage

The major constraint to grain storage is related to the handling and transport of grains. Historically, grains have been stored in jute or HDPE bags of 100 kg capacity, while the on-farm storage of grains is done through cover and plinth (CAP) storage and not through heap storage as used in the past. CAP storage was mainly used to store paddy and wheat obtained from farmers. CAP storage has been tested as a method for temporary storage of wheat and paddy for 3-6 months according to Omobowale *et al.* (2016). The process of CAP storage involves forming a raised plinth about 0.6 m (2 ft) above the ground, over which food grains, in the form of bags, are stacked in a dome and then covered from the top and sides

with a 250-micron LDPE sheet. Generally, wheat, maize, paddy, and sorghum grains are stored in the CAP for 3-6 months. It is an economical storage structure that takes less than three weeks to prepare. Nigerian farmers store around 65-70% of their rice and wheat for human consumption, feed, or seed, and sell the rest through Krishi Mandis (government/private sellers).

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 (Abbas *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 *et al.* (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 Lopez-Castillo *et al.* (2018a), 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, 2006), 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 *et al.*, 2012).

Similarly, the effects of temperature, relative humidity, and moisture content on the germination percentage of grains stored in various storage facilities are important (McNeil *et al.*, 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.

Postharvest Losses Due to Pests

The increase in resistance to pests during grain storage has prompted the study of peroxidases as a trait that can be used in maize breeding to obtain maize with higher pest resistance (Lopez-Castillo *et al.*, 2018b). Antibiosis, antixenosis, and preference have been identified as the main mechanisms of resistance of maize grains to attacks by *S. zeamais*. The crude fibre, phenolic acids, and trypsin inhibitors in whole-grain maize were found by Neme and Mohammed (2017) to be sources of resistance, where higher levels of these biochemicals lead to lower infestation. Nevertheless, knowledge of natural resistance to pests remains insufficient, particularly regarding the specific roles of certain biochemical factors, such as peroxidases and phenolic acid amides. Therefore, further studies are needed to develop future breeding programs and prevent insect losses after harvest, thereby increasing food security in countries at risk.

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 *et al.* (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 *et al.*, 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 *et al.*, 2017).

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 *et al.*, 2004).

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.

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, 2006), 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	Salmonella, Escherichia coli, Bacillus cereus, Erwinia herbicola, Xanthomonas campestris, Azotobacter, Pseudomonas, Micrococcus, Lactobacillus	Laca et al. (2006); Harris et al. (2013)
Filamentous fungi and yeasts	Eurotium, Aspergillus, Penicillium, Rhizopus, Mucor, Alternaria, Cladosporium, Fusarium, Helminthosporium, Sporobolomyces, Rhodotorula, Hansenula, Torulopsis, Candida, and Saccharomyces	Harris et al. (2013); Pitt and Hocking (2009); Bullerman and Bianchini (2009)

Table 3: Mycotoxins in Cereal Grains

Mycotoxin	Fungal Source(s)	Effects of Ingestion for Humans	Commodity
Deoxynivalenol/Nivalenol	Fusarium graminearum, Fusarium crookwellense, Fusarium culmorum	Human toxicoses e.g. nausea, vomiting, diarrhoea, headache, fever	Wheat, maize, barley
Zearalenone	Fusarium graminearum, Fusarium crookwellense, Fusarium culmorum	Identified by the International Agency for Research on Cancer (IARC 1994) as a possible human carcinogen	Maize, wheat
Ochratoxin A	Aspergillus ochraceus, Penicillium verrucosum	Suspected by IARC as human carcinogen	Barley, wheat, and many other commodities
Fumonisin B1	Fusarium moniliforme 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 et al. (2015); 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 et al. (2010). Magan and Aldred (2006)
Debranning	Process during which the bran layers are removed from the endosperm by friction and abrasion	Not completely suitable for wheat due to the crease on wheat kernels; whole-grain demand in the market	Laca et al. (2006)
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 et al. (2005); Andrews et al. (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); Farkas et al. (2014)

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.

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, dehiscing, 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.

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.

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 (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.

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.

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.

Studies on Essential Oils in Active Packaging

Tsitlakidou et al. (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.

Studies on Molecular Mechanisms and Safety Profile

According to Pisoschi et al. (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.

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 *et al.*, 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).

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.

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 *et al.*, 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.

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.

Recent Technological Innovations

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).

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.

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.

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.

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 (Amiri *et al.*, 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 (Sheik *et al.*, 2024).

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):

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.

Formation of Nanoparticles

Several methods are available for forming nanoparticles, described below.

Ionic Gelation

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

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.

Coacervation

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

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 *et al.*, 2025).

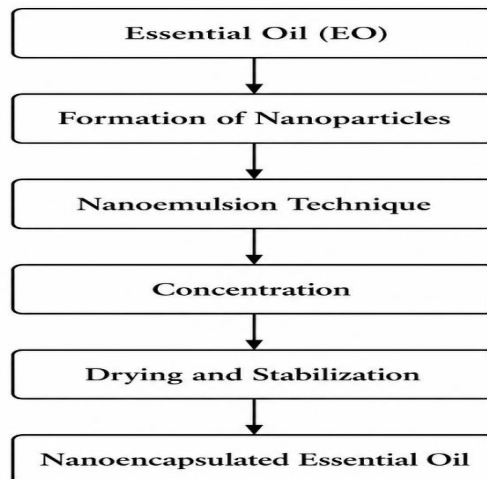


Figure 1: Flow Chart Illustrating the Preparation of Nanoencapsulated Essential Oil (EO) Through Nanoparticle Formation Using the Nanoemulsion Technique, Followed by Concentration, Drying, and Stabilization to Obtain the Final Nanoencapsulated Product. Adapted from Li *et al.* (2025)

Advantages of Nanoencapsulation for Stored Cereal Grains 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 (Amiri *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).

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).

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 (Sheik *et al.*, 2024). It is especially beneficial in hermetic storage systems because of vapor release.

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 Amiri *et al.* (2021), after six months, encapsulated clove essential oil maintained more than 80% of its antioxidant activity, whereas free EO lost about 40%.

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).

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.

Key Challenges in Applying Nano-encapsulated Organic Preservatives

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 *et al.*, 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).

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 (Sing, 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 (Weisany *et al.*, 2022; Singh, 2021).

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 (Teruel-Jofre *et al.*, 2022).

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, 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, 2021).

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 *et al.*, 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).

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.

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 *et al.*, 2021). Conversely, ethanol

acts mainly as an antimicrobial agent through protein denaturation, dissolution of lipids in the membrane, and interference with metabolic processes (Sweet *et al.*, 2024) of microorganisms.

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.*, 2008). 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.

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-flavoured drinks, for example, the combination of D-limonene and ethanol would allow enjoying the natural flavour 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).

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.

CONCLUSION

Collectively, the evidence reviewed indicates that organic preservatives particularly essential oils rich in thymol, eugenol, carvacrol, and cinnamaldehyde provide broad-spectrum antimicrobial, antifungal, antioxidant, and insect-repellent protection for stored cereal grains, and that

nanoencapsulation substantially improves their stability, controlled release, and sensory acceptability relative to free oils. But realizing this potential on a large scale is not merely about laboratory proof of effectiveness; rather, it involves the development of a comprehensive approach which combines cost-effective essential oils with affordable encapsulation techniques appropriate for small-scale and mid-scale grain storage facilities, especially in the developing countries where the rates of postharvest losses are the highest. In combination with harmonized regulation at the international level, such an approach could contribute significantly to the reduction of the postharvest loss from fungal spoilage, mycotoxins, and insect infestation, thus helping to achieve Sustainable Development Goal 2 (Zero Hunger) and Goal 12 (Responsible Consumption and Production). Three approaches need to be developed simultaneously: (i) standardization of formulations for essential oils using chemotyping and analytical quality control; (ii) decreasing of the cost of encapsulation by using locally produced carriers and simpler process flows; (iii) development of harmonized standards and labelling systems for food-grade nanoencapsulated preservatives. The coordinated effort in these three areas rather than the continuous efficacy trials will define the future of organic preservatives for grain security.

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