Review Article

A Review on the Potential of Organic Preservatives in the Preservation of Grains

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ABSTRACT

The goal of agricultural produce preservation is to minimise post-harvest losses while maintaining food security. Grains are essential food items that are consumed by people all over the world. However, their storage and long term preservation are severely hampered by postharvest losses brought on by microbial infection, insect infestation, and environmental conditions. Synthetic chemical preservatives have historically been used to reduce these losses, but growing interest in safer, environmentally friendly substitutes is a result of the risks they pose to human health and the environment. Significant antibacterial, antifungal, and antioxidant qualities have been shown by organic preservatives, which are made from natural or organic sources like plants, microbes, and animal based products. Typical examples include plant extracts from garlic and ginger, microbiological agents like bacteriocins, and essential oils from clove, thyme, and neem. These compounds improve the safety and shelf life of grains that are stored in addition to preventing the growth of spoilage organisms. Organic preservatives provide a number of several benefits over their synthetic counterparts, such as low toxicity, biodegradability, and consumer acceptability. In regulating storage pests and spoilage fungi in grains including maize, rice, wheat, and sorghum, organic or natural preservatives can be useful, according to the results of numerous scientific studies highlighted in this study. Their widespread acceptance is still constrained, nevertheless, by problems with cost, availability, standardisation, and consistent efficacy in various environmental settings.

Keywords: Cereal Grains, Food Preservation, Organic (Natural) Preservatives, Chemical Preservatives, Post-Harvest Losses.

INTRODUCTION

To extend the shelf life of foods like grains, fruits, vegetables, prepared foods, cosmetics, and medications, as well as to maintain their quality and safety, preservatives which can

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be synthetic or natural (organic) are added to agricultural produce. They do this by preventing, delaying, or halting microbial contamination, fermentation, acidification, and decomposition. Many meats, such as fish and hams, are still preserved by salting. It is believed that jams and jellies contain a lot of sugar. The Eastern Civilisations of China and India also used spices to preserve their food. To preserve vegetables, pickling them in salt, vinegar, lemon juice or mustard oil was a frequent method. In the early 19th century, canning and pasteurisation changed food preservation; irradiation, filtration, and addition are examples of modern sterilisation methods [1]. Enhancing food safety and quality is essential. Since the dawn of time, humans have enhanced their diet and hunting methods, tamed plants and animals, preserved food physically, and added molecules to food to alter its flavour or prolong its shelf life [2]. Over time, many ingredients have played vital roles in a wide range of cuisines, providing an inexpensive, nutrient-dense, delicious, colourful, and safe food supply. Food additives and technological improvements have also played important roles. Their use in the food industry is essential because it makes it possible to reduce loss, improve quality, extend shelf life, develop novel formulas, and standardize all of which contribute to meeting the market's ever-increasing demands [3]. Since food preservation ensures that food products are constantly safe and edible, it is a crucial part of the food industry. Synthetic and natural (organic) preservatives have been developed and enhanced along with a variety of preservation methods, greatly increasing the shelf life of food products. Several methods, such as heating, chilling, salting, drying, and synthetic chemicals, are used to keep food safe from rotting bacteria and extend its shelf life [4]. Among the first methods for food preservation and spoiling prevention that are frequently used are chemical preservatives. The growth of bacteria and fungus that can contaminate food is inhibited by chemical preservatives. Concern over the possible health dangers of chemical preservatives is growing, despite the fact that they have effectively stopped microbial development and extended the shelf life of food products [5]. Chemically synthesised preservatives are prohibited due to their potential carcinogenicity, even though they have strong antibacterial activity. It is now more crucial than ever to find safe, effective, and natural or organic food preservatives that can protect against chronic illnesses and improve food product safety for decades. Reviewing the potential of natural (organic) preservatives in the preservation of cereal grains is the aim of this research.

LITERATURE REVIEW

Cereals

One of the most significant agricultural products in the world, cereals are used as the primary ingredient in animal feed and as nourishment for humans. Prehistoric agriculture development was closely linked to the domestication of cereal grains, and most civilisations have relied on cereals for the majority of their food supply since they were first cultivated [6]. Cereal grains make up almost 60% of the world's cultivated land and are the most widely consumed food group [7]. Over the past 50 years, global cereal output and yield have expanded to satisfy the demands of a growing global population. Maize, rice, wheat, barley, sorghum, millet, oats, and rye are the main kinds of cereal grains [8]. The air, dust, soil, water, insects, rodents, birds, animals, germs, people, storage and shipping containers, and handling and processing equipment are the main environmental causes of grain contamination. Although microbiological contamination accounts for the majority of contamination, heavy metals and industrial pollutants also contribute. Mycotoxins, or secondary metabolites made by fungi that can grow on grain, are among the most harmful substances found in a variety of food products [9]. Certain moulds have the ability to produce toxic mycotoxins, which could seriously endanger consumers' health. Moulds and mycotoxins are thought to cause 5-30% of cereal grain losses during storage, whereas insects and rodents cause 5% and 2% of losses, respectively. The average yield loss for industrialised and developing nations is 1% and 10%–30%. Grain has a great diversity of possible spoilage organisms in its microbial load, which varies depending on the climate during growing. Transport-related post-harvest contamination is also a possibility. Bacteria, yeasts, and filamentous fungus from numerous genera make up this microbial burden. Various factors influence the activity of these microorganisms during storage and, consequently, the crop's shelf life. Water availability during storage and moisture content are two of the most important factors. Since grains have a water activity of less than 0.70 and low moisture contents of 12-13%, they are typically kept using modern techniques such osmosis, salt, sugar, oil, sun drying etc.

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Organic *vs* Inorganic Preservatives

Organic preservatives

Organic preservatives, also known as natural preservatives, are substances that come from plants, microorganisms, or animals and aid in delaying oxidation, preventing microbial growth, and preserving food items without the use of artificial chemicals. Organic preservative research has accelerated thanks to the growing demand for clean-label goods and growing health concerns about chemical additives [10]. Bioactive substances with potent antibacterial, antifungal, antioxidant, and insect-repelling qualities, including phenolics, flavonoids, terpenoids, and essential oils, are abundant in these natural agents. Organic preservatives are used in cereal grain preservation to stop the growth of mould, insect infestation, rancidity, and mycotoxin production all of which lead to large postharvest losses. Numerous studies have demonstrated the efficacy of compounds produced from plants. For example, Aspergillus flavus and Fusarium spp., the main fungi linked to cereal spoiling, have been shown to be strongly inhibited by clove oil (rich in eugenol), neem extract (azadirachtin), and thyme oil (thymol) [11]. Additionally, it has been discovered that these bio-preservatives deter grain beetles and weevils, which are prevalent in the storage of rice and maize [12]. In a comparative investigation, Alabi et al. [13] discovered that extracts of ginger and garlic considerably decreased the fungus load in sorghum that was held for more than six months, surpassing even certain commercial chemical preservatives. In a similar vein, Adekunle and Essien [14] found that a mixture of cinnamon extract and lemongrass oil increased the shelf life of wheat that was stored by lowering the amounts of free fatty acids and mould. Organic preservatives are environmentally benign, biodegradable, and generally recognised as safe (GRAS), in contrast to synthetic preservatives [15]. But issues like instability, limited shelf life, and inconsistent efficacy across storage settings still exist [16]. In order to improve their stability and controlled release, more stable formulations have been developed, such as those involving microencapsulation and emulsification. Blending several plant extracts to provide synergistic effects has been the subject of recent advances. Similar evaluations of the application of fermented bacteriocins produced from Lactobacillus in maize storage were conducted by Chikere and Odu [17], who found notable antibacterial activity without compromising grain quality. When it comes to grain preservation, organic preservatives present viable substitutes for synthetic ones. Particularly in underdeveloped nations, better, more economical, and sustainable solutions for food security may result from further research and development of these bioactive compounds.

Synthetic preservatives

Synthetic preservatives are artificial chemical substances that are added to food and agricultural products to stop oxidation, microbiological spoiling, and quality deterioration while they are being stored. Because they are readily available, inexpensive, and highly potent, they have long been used extensively in cereal grain preservation [18]. These preservatives are essential for preserving the safety and shelf life of grains such barley, sorghum, rice, wheat, and maize. Sorbic acid, sodium benzoate, calcium propionate, butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), and sulphites are typical examples. These substances prevent the growth of bacteria that cause spoiling, including Aspergillus, Penicillium, Fusarium, and insects that infest grains [19]. Calcium propionate is frequently used in bread and cereal goods to stop mould growth and increase shelf life by up to 60 days [20]. Another popular preservative, sodium metabisulfite, works well to keep bacteria and fungus in milled rice and maize under control while they are being stored [21]. But because of their possible health hazards, such as cumulative toxicity, allergic responses, and carcinogenicity, synthetic preservatives have drawn more attention [22]. Numerous studies have shown that prolonged use of synthetic chemicals can cause negative side effects as dermatitis, respiratory irritation, and even disturbance of the gut microbiota [23]. In order to reduce these hazards, some nations have set maximum allowed limits (MAL) on the amount of specific preservatives in food. For example, BHT and BHA are being reviewed by the U.S. FDA and are regulated in certain food products in the European Union [24]. The global grain storage market is nevertheless dominated by synthetic preservatives despite these reservations because of their affordability, extended shelf life, and broad-spectrum activity. According to Guan et al. [25] BHA storage of wheat produced a mould infestation of less than 2% over 180 days in tropical settings, which was a substantial improvement above untreated controls. However, recent research indicates that an excessive dependence on synthetic preservatives may result in environmental persistence and microbial resistance, which has prompted recommendations for integrated solutions that mix organic agents with lower synthetic dosages [26]. This hybrid strategy has the potential

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to lower chemical loads without sacrificing effectiveness. Although synthetic preservatives are effective methods for preserving grains, there are legitimate worries about their effects on the environment and human health. To ensure sustainable grain storage, their continuous usage should be governed by stringent regulations, toxicological evaluation, and perhaps supplemented with natural alternatives.

The comparative benefits of organic and synthetic preservatives are displayed is Table 1 [1].

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.	Olden Tech [27]: Natural preservatives are biodegradable and derived from renewable resources, contrasting with synthetic preservatives that can contribute to ecological harm.
2.	**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 a desire for natural ingredients.	The Earth Reserve [28]
3.	**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 a negative perceptions.	Wiley Online Library [29]
4	**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.	ACS Publications [30]
5	**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.	Allied Academies [31]
6	**Environmental Impact**	Lower environmental footprint due to natural sourcing and biodegradability.	Production and degradation can contribute to pollution and carbon emissions.	Allied Academies [31]: Natural preservatives have a much lower environmental footprint compared to synthetic ones.
7	**Flavour Enhancement**	Can enhance the flavor profile of foods (e.g., herbs and spices) while providing preservative effects.	May not contribute positively to flavor and can sometimes impart undesirable tastes.	ETprotein [32]

Hurdles in Grain Storage

Grain transportation and handling are the primary bottlenecks. Typically, 100 kg HDPE or jute bags are used to store grains. Grain was also stored on farms using plinth and cover storage, as opposed to heap storage in the past. This occurs throughout the food grain storage and procurement processes, as well as during evacuation and transportation to the appropriate locations. This system was mainly used to store wheat and paddy that were purchased from farmers. A tried-and-true method for temporarily storing wheat and paddy for a brief period of time is CAP storage. According to Omobowale et al. [33], CAP storage entails building an elevated platform that is roughly 0.6 meters (2 feet) off the ground, on which food grain sacks are stacked in a dome pattern. The top and all four sides of the stacks are covered with 250 micron LDPE coverings. Food grains like sorghum, wheat, maize, and paddy are typically kept for three to six months. It is the most cost-effective storage system and is frequently utilised for bagged grains in Haryana. In less than three weeks, the construction can be constructed.

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About 65 to 70 percent of the rice and wheat that Nigerian farmers harvest is kept for human consumption, animal feed, or seed. They sell their food grains in Krishi Mandis, which are open to both public and private merchants. Depending on the farmer's holding capacity, surplus grain, and farm holding size, the bigger percentage is kept at the farm level.

Postharvest Spoilage of Cereal Grains

Major postharvest losses occurring in grain considered by farmers are weather (40%), field damage (33%) and storage pests (16%) as the three most important factors causing poor crop yields and aggravating food losses. However, survey results suggest that the farmers' poor knowledge and skills on postharvest management are largely responsible for the food losses [34]. There is need for technical knowledge of the farming systems in relation to climate variability to minimize postharvest losses. Also necessary trainings on postharvest management can reduce food losses and improve poverty and household food security. As reported Jain et al. [35] major physiological, physical and environmental causes of postharvest losses are high crop perishing ability, mechanical damage, excessive exposure to high ambient temperature, relative humidity, rain, contamination by spoilage through fungal and bacteria, invasion by birds, rodents, insects and other pests and inadequate handling, storage and processing techniques. In current time contamination through mycotoxins is also found in urban areas. Lopez- Castillo et al. [36] reported that mycotoxins are poisonous compounds produced by certain species of fungi found in contaminated grain. There are five major groups of mycotoxins which can occur in grains *viz* aflatoxin, fumonisin, deoxynivalenol (DON), ochratoxin (OT) and zearalenone (ZEN). Their occurrence may start in the field during harvesting, handling, storage and processing. To avoid this spoilage best aeration of grains must be adopted [37]; this aeration of grains can be done by installing horizontal fan in the bins and silos. By keeping air flow rates and fan control methods, best results to avoid spoilage could be obtained for aerated wheat stored in round bins and large horizontal storages under tropical and subtropical climatic conditions. To improve food quality, ozone is a strong oxidant and has different food applications to ensure food safety. Ozone treatment is considered an ecofriendly and cost-effective food processing technique. Ozone has great potential to improve the functionalities of grain products while ensuring food safety. The impact of ozone treatment on the composition (eg mycotoxins) and physico- chemical properties of components (eg starch and protein) of different food grains (eg wheat, rice and maize) has been studied by Zhu [38] who concluded that the rheology, colour, storage and germination capacity of the grains are affected by ozone. Besides spoilage, presence of moisture content and broken kernels in postharvest grains effects the initial bulk density of the grain and grain compaction under overburden. For grains, the initial bulk density is inversely affected by grain moisture while packing increases slightly with grain moisture. If we consider the increase in broken kernals of the grains, this initial bulk density of grain decreases further with the grain moisture and the interaction of broken grain particle size and concentration results in increased volume of grain storage [39].

Similarly effect of temperature, relative humidity and moisture content on germination percentage of grain stored in different storage structures is also significant [40]. In the grain storage structures grain moisture content increases as compared to ambient moisture. Similarly, temperature in grain storage structure also gets increased as compared to ambient temperature. It has been observed that germination percentage of the grain decreases in all the grain storage structures despite the fact of increase in relative humidity inside. This happens due to inadequate aeration system in the grain storage system.

Postharvest losses due to pests

Grain resistance to pests has advanced to unprecedented levels in recent years. For instance, research on maize suggests that peroxidases could be used as a breeding feature to create types that are more resistant to storage pests [41]. Similarly, the mechanisms of maize grain resistance to Sitophilus zeamais attack were antibiosis, antixenosis, and preference. Crude fibre, phenolic acid, and trypsin inhibitor of whole-maize grain were found to be the foundations of resistance by Neme and Mohammed [42]. Low infestation was the outcome of their notable growth in grains. We still don't know much about natural pest resistance, though. It is still unknown what the precise role of biological components such phenolic acid amides and peroxidases is. To further inform future breeding programs, more extensive and in-depth research in this area is required. Future breeding initiatives aimed at reducing postharvest insect food losses and promoting global food security, with a focus on vulnerable nations, would benefit greatly from this understanding [43].

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Efficiency of components of storage

In every grain storage facility, there was an inadequate aeration rate and no fan control. Relative humidity, ambient temperature, and grain moisture are all less or not controlled when grains are stored. This calls attention to better grain storage practices that reduce postharvest grain loss. Hosakoti et al. [44] stated that in order to assess grain temperature and moisture at various points within a storage structure in addition to ambient temperature, it is advised to build appropriate sensors for online monitoring of grain moisture and temperature inside the storage structures.

It is highly advised to promote solar power in grain storage components and to control them using environmental variables. For instance, using a humidistat to regulate a solar-powered DC fan for grain drying is an example of this [45]. A photovoltaic-powered DC fan was controlled by a low-cost, low-energy microcontroller-based humidistat. To check if the humidistat was operating as intended, measurements of the fan current and voltage, insulation, ambient temperature, and relative humidity were taken every five minutes. The primary determinants of the mass flow rate in the storage system during design were drying temperature, drying duration, and cooling type [46].

Design and fabrication of components of storage

Farmers may be able to lower postharvest losses by using hermetic storage containers such metal silos, which are airtight and soldered, and super grain sacks, which are composed of high density polyethylene to minimise gas exchange. The metal silos are highly efficient, but they are also costly. The cost per kilogramme of grain held drops as the container's volume increases because the metal sheet accounts for half of their cost. Therefore, to ascertain the size at which silos become cost-effective under various price situations, economic research is required [47]. Given the shortcomings of grain storage structures, which have been partially ascribed to the high cost and scarcity of building materials, it is recommended that termite mound clay (TMC), which is easily accessible, be used to construct grain silos rather than traditional galvanised steel (GS) and reinforced concrete (RC) silos for grain storage in the humid tropics [33]. Grain in underground pits absorbs moisture from the environment, which leads to the growth of insect pests and storage fungus, which are nearly consistent in distribution under static conditions. Then, when the silo is being emptied, it falls. These pressures fluctuate in response to surges in the silo and changes in the silo and hopper's dimensions; they are sensitive to biophysical processes and the surrounding environment. Grain for sorghum is stored underground [48].

System of the silo-hopper storage

According to Ruiz et al. [39] who examined the silo's pressure theory and storage mechanics, only two forms of pressure reliably function when silos are designed, regardless of their size, shape, or material. Normal wall pressure comes first, followed by the material's vertical pressure while it is being stored. When the silo is filled and emptied, this typical wall pressure is created. When the silo is being filled and emptied, it is not kept constant. A thorough understanding of its physics is necessary, particularly during surges inside the silo. However, because of the release of frictional forces, this normal pressure drops throughout the extended storage duration.

These two pressures have no effect on the grain material's horizontal thrust. For silo normal wall pressure, the universal mechanics can be expressed as follows: Similarly, when the silo is fully filled, the grain material exerts its maximum vertical pressure, expressed as follows:

$$Silo\ vertical\ pressure = \frac{Specific\ weight\ of\ the\ grain\ X\ volume\ of\ the\ grain\ in\ the\ silo}{Unit\ of\ length\ at\ each\ time\ (t)x\ perimeter\ of\ the\ silo}$$

$$Silo\ normal\ wall\ pressure = \frac{frictional\ force\ of\ the\ grain\ on\ the\ wall}{Surface\ area\ of\ the\ wall\ on\ which\ it\ is\ acting}$$

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Sources of Microbial Contamination of Cereal Grains

Cereal grain microbial contamination happens throughout crop growth, harvest, postharvest drying, and storage [49] and can come from a variety of sources, including as air, dust, water, soil, insects, rodents, and birds' excrement, as well as contaminated equipment and unhygienic handling. In addition to unsanitary handling, harvesting and processing equipment, and inadequate storage conditions, environmental factors including drought, rainfall, temperature, and sunlight also have a significant impact on the kind of microbial contamination, which differs depending on the growing location [50].

Increased precipitation right before harvest is one of the factors that causes *Alternaria spp*. to colonise the grain ears extensively, resulting in black fungal discolouration that may be seen on the kernels' surface as well as underneath the pericarp. Table 2 [2] lists the sources of microbial contamination in cereal grains. Table 3 also displays mycotoxins found in cereal grains [3]. Table 4 [4] displays the current cereal grain preservation technique.

Table 2: Cereal Grain Microbial Contamination Sources

Type Of Microorganisms	Name of Microorganisms	References
Bacteria	*Salmonella, Escherichia coli, Bacilluscereus, Erwinia herbicola, Xanthomonas, campestris, Azotobacter, Pseudomonas, Micrococcus, Lactobacillus*	Harris et al. [51]
Filamentous fungi and yeasts	*Eurotium, Aspergillus, Penicillium, Rhizopus, Mucor, Alternaria, Cladosporium, Fusarium, Helminthosporium, Sporobolomyces Rhodotorula, Hansenula, Torulopsis, Candida, and Saccharomyces*	Harris et al. [51]

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 human carcinogen	Maize

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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 - molds (fungicides), weeds (herbicides) and insects (insecticides)	High environmental impacts Direct negative impact on human health Increasing resistance against pesticides	Liu et al. [52]
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. [53]
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 the wheat kernels Whole-grain demand in the market	Laca et al. [54)]
Chlorine and hypochlorite	Due to their oxidizing capacity, chlorine and hypochlorite treatments are one of the most widely used processes for microbial control	Low inactivation of fungal spores on cereal grains and generation of toxic by-products after the treatment	Delaquis and Bach [55]
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. [56]
Ozone	Triatomic oxygen formed by addition of a free radical of oxygen to molecular oxygen	The cost of treatment can be relatively high due to complex technology	Greene et al. [57]

Table 5: Potential Methods and Technologies for Cereal Grains Preservation

Method/ Technology	Description	Limitations	References
Microwave (MW) treatment	Electromagnetic waves with frequency within 300 MHz to 300 GHz; microbial inactivation based mainly on thermal effect	Seed viability and seedling vigour can be decreased after the treatment Higher microbial reduction levels in presence of other stresses, such as acidic pH or increased temperature	Chandrasekaran et al. [58]
Pulsed UV light	Short-duration, high-power pulses of a broad spectrum of white light from the UV (50% of the spectrum), to the near infrared region	Low ability to penetrate grains because of their irregular and complex surface can decrease germination rate of the seeds	Maftei et al. [59]
Non-thermal (cold) plasma	Partially ionized gas consisting of highly reactive chemical species	Efficiency of the method depends on the specific properties of the food product and its surface	Schluter et al. [60]
Organic acids	Antimicrobial agents due to the reduction of the environmental pH	Can increase moisture content and penetrate into the endosperm of grains	Sabillon et al. [61]

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Agricultural crops like cereals will play a crucial role in meeting this growing nutritional need, given their long history as global staples of the human diet and livestock feed. However, global agricultural area is limited, making it difficult to expand cereal production. Given that microbial pests cause about 15% of all cereals worldwide to be lost, the most sensible way to combat this issue is to increase both food safety and sustainability to reduce economic losses. This was made possible by the rapid growth of the world's population.

Microbial spoilage of grains both before and after harvest is one of the main causes of crop loss worldwide. Several methods for avoiding microbial contamination in the field have been examined and studied. The possibility of contamination cannot be totally eliminated, nevertheless, even with the greatest management techniques. Cereals always have a certain microbial burden when harvested due to the environment's constant and pervasive presence of microbes and fungal spores. Furthermore, environmental factors that are beyond human control, including humidity and temperature, may be critical for mould infestation. Therefore, in order to prevent microbiological spoilage, proper post-harvest crop treatment both before and during storage is just as crucial as pre-harvest measures.

Grain Storage

Conservation of biodiversity in terms of grain storage nowadays is essential due to cultural heritage and health of the state. This session draws the attention towards the re-evaluation of traditional grain storage structures in terms of biodiversity and its allied branch of knowledge, pre-storage loss during drying and cleaning was higher than the loss during the storage. Average storage cost per quintal per year is maximum among the gunny bags lined with polythene sheet and minimum in case of underground storage. Similarly, postharvest implements also cause loss in grains so only cereals are threshed by machines as compared to pulses which are threshed manually. There have been reports of grain loss in tractor and bullock cart transporting. Grain loss was also a result of post-threshing procedures such as sieving, according to Nwosu [62]. These losses are very similar to grain losses in storage caused by rodents, insects, and microbes. Currently, spontaneous contamination of food grains accounts for 30% of grain loss [62]. The biodiversity of microorganisms and pests makes the use of bio-insecticides ineffective. Grain loss during storage was thought to be limited to rodent damage in primitive times, which is wildly inaccurate. Grain loss in storage is also caused by other environmental conditions, such as the presence of moisture, a humid atmosphere, and bio-temperatures that are conducive to the growth of microorganisms and pests. When analysing grain damage during storage, the atmospheric conditions both before and during storage are crucial. The quality and nutritional worth of stored grains can be lost due to discolouration, odour emission, loss of germiability, and other critical nutritional and medicinal qualities that are not noticeable by ordinary human conduct.

In Nigeria, the most common crops kept in storage facilities include beans, sorghum, sesame, soybean, groundnuts, maize, wheat, barley, paddy, and millets. Typical grain storage structures include metal bins, subterranean storage, piles of grains in a room, fertiliser bags, jute bags, polythene/plastic bags, and gunny bags.

Material and methods for grain storage

The metabolism of pests and insects is impacted by the storage of grains in either an airtight or air free environment, as is the case with hermetic storage [63]. The mechanism of carbon dioxide and oxygen depletion in hermetic storage causes carbon dioxide to accumulate and oxygen to be depleted from the storage as a result of grain breathing or other biotic or abiotic sources. Because of the oxygen shortage that arises, there is a buffer of carbon dioxide and oxygen in the hermetic storage to enable the grain, such as wheat, to breathe. Nigerian rural communities frequently use open sun and shadow drying techniques, which reduce grain water activity and raise grain kernel hardness. In Nigeria, threshing, winnowing, cleaning, drying, bagging, ponding, dehusking, and decotification are all steps in the grain storage process. Quantity of grains, purpose (commercial, household, or seed), time period, storage location, treatment (such as fumigation or disinfection), frequency (such as terations from the bins/silos), control measures and preparedness (such as dampness, humidity, temperature, etc.), and quality are the goals and purposes of grain storage structures worldwide [64].

Studies in the Use of Organic Preservatives

Significant advancements have been made in the last few years in the investigation and use of organic preservatives in food systems, especially with regard to the preservation of grains and cereals.

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Studies on essential oils as functional food preservatives

The use of essential oils (EOs) as functional food preservatives was thoroughly reviewed by Singh [65]. Singh investigated the antibacterial and antioxidant properties of several essential oils, including cinnamon, thyme, oregano, and clove. Their capacity to prevent oxidative spoiling and a variety of foodborne infections was noted by the author. Nevertheless, issues such high volatility, potent scent, limited water solubility, and uneven antibacterial efficacy in various food situations were noted. Singh suggested cutting edge delivery techniques like nanoformulation and microencapsulation to get over these restrictions. By providing better stability and regulated release, these methods lessen their influence on the senses. Essential oils require formulation engineering for optimisation, notwithstanding their potential as natural substitutes for synthetic chemicals. Particularly in grain-based food applications, Singh [65] underlined the significance of additional study into encapsulation, sensory acceptance, and accurate dosing.

Studies on nano encapsulation of essential oils in cereal grains

The study by Maurya et al. [66] concentrated on essential oils that were nanoencapsulated for the purpose of protecting cereal grains after harvest. Their review focused on how to remedy the instability and volatility of free essential oils by encapsulating them in biopolymeric matrices such chitosan, alginate, and cyclodextrins. These nano formulations showed reduced loss of active chemicals and sustained antibacterial effect, as the authors showed.

However, Maurya et al. [66] also covered important obstacles such the impact on grain germination and sensory qualities, regulatory uncertainties around food-grade nanoparticles, and the high cost of manufacture. Notwithstanding these reservations, the review found that by delivering a steady and prolonged release of bioactive chemicals, nanoencapsulation greatly improves the safety and shelf-life of grains that are stored. The authors demanded harmonisation of nanoparticle standards for use in food, safety validations, and pilot size applications. Their suggestion emphasises the necessity of a multidisciplinary strategy that incorporates policy frameworks, food science, and nanotechnology.

Studies on essential oils in active packaging

Tsitlakidou et al. [67] investigated the incorporation of essential oils into materials used for active food packaging. The application of edible films and coatings containing EOs was examined in their review, with special attention paid to chitosan, whey protein, and biodegradable polymers. Evaluating such packaging technologies' ability to deliver regulated EO release and prolong the shelf life of grains and cereal products was the goal. Finding a way to evenly distribute EOs in films without sacrificing consumer safety and mechanical strength was one of the main challenges found.

Nonetheless, noteworthy innovations were documented in which coatings infused with essential oils demonstrated potent antibacterial properties and preserved food quality in a variety of storage scenarios. The authors came to the conclusion that active packaging offers a fresh, eco-friendly approach to grain storage. Developing scalable coating technologies and testing their effectiveness in actual storage conditions were among the recommendations, especially for low-income settings where synthetic preservatives would not be feasible.

Studies on molecular mechanisms and safety profile

The chemical processes and safety profile of essential oils as environmentally friendly preservatives were thoroughly examined by Pisoschi et al. [68]. The study concentrated on the ways that substances found in essential oils, such as carvacrol, eugenol, and cinnamonaldehyde, cause membrane disruption, cellular contents to leak out, and oxidative stress to induce their antimicrobial effects. The review brought up issues with allergenicity, dosage management, and variability in EO composition due to plant source variances, even if the effectiveness was well validated by in vitro and in vivo investigations. Crucially, the authors highlighted new developments in computational biology that enable the prediction of EO toxicity and action. This invention represents a significant advancement that enables safer, more focused uses. According to the findings, essential oils have the potential to replace synthetic preservatives if thorough safety assessments are implemented. To encourage their wider usage in grain preservation, the authors suggested standardising EO chemotypes, harmonising international regulations, and integrating them with risk models for food safety. When taken as a whole, these research show a consistent tendency towards the creation of organic preservatives that are safe, efficient, and

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ecologically friendly. The field has advanced greatly in recent years, starting with Singh's early investigation of functional essential oils and continuing with the discoveries made by Maurya et al. [66] regarding nanoencapsulation. The use of EOs in active packaging systems, along with the increasing complexity of safety and molecular analysis, indicate that organic preservatives are becoming a mainstream research and development priority rather than a niche idea. Future initiatives should focus on consumer acceptance research, extensive field applications, and ongoing technology transfer funding to guarantee that these advancements are implemented in actual grain storage and food supply systems.

Bioefficiency of Organic Preservatives in Protecting Stored Cereal Grains

Cereal grains, including wheat, maize, rice, barley, sorghum, millet, and oats, are the foundation of global food security, contributing a significant proportion of daily caloric intake in most regions. However, after harvest, these grains face a multitude of threats during storage, such as microbial contamination, mycotoxin production, insect damage, oxidative rancidity, and nutrient loss. Post-harvest losses in cereals can reach between 10 - 30% in developing countries, translating to billions of dollars in economic loss and substantial impacts on food availability (69). Effective preservation systems are therefore essential not only for maintaining food safety and nutritional quality but also for sustaining the livelihoods of producers and ensuring market stability. Traditional preservation techniques such as drying, hermetic storage, and application of synthetic chemical preservatives have played important roles in reducing spoilage. However, over-reliance on synthetic agents such as propionates, benzoates, and sorbates has raised public health and environmental concerns. Several studies have linked chronic exposure to synthetic preservatives with allergic reactions, carcinogenic risks, microbiome disruption, and ecological toxicity (70). Moreover, resistance development in spoilage organisms has been observed following prolonged use of certain synthetic fungicides and bactericides, further reducing their long-term effectiveness. The search for safer, eco-friendly, and consumer-acceptable alternatives has led to increased interest in organic preservatives compounds derived from plant, microbial, or animal sources that are biodegradable, generally recognized as safe (GRAS), and capable of protecting stored grains without contributing to environmental pollution. Organic preservatives, particularly essential oils (EOs) and organic acids, have emerged as promising solutions. Their natural origin, multi-target antimicrobial activity, and compatibility with clean label food trends make them attractive both to consumers and regulatory bodies (71). "Bioefficiency" in this context refers to the ability of these natural agents to inhibit or suppress spoilage agents, delay chemical deterioration, and maintain the sensory and nutritional qualities of grains over extended storage periods. The bioefficacy of organic preservatives is determined by their chemical composition, stability during storage, method of application, and interaction with grain matrices. Modern research is exploring new formulation strategies such as nanoencapsulation, emulsification, and active packagingt o overcome limitations such as volatility and instability (72). Mechanisms of Bioefficiency is given as thus.

Antimicrobial and Antifungal Action

One of the primary mechanisms by which organic preservatives protect stored cereal grains is through antimicrobial activity. Essential oils such as thyme, clove, oregano, cinnamon, and carnation contain high concentrations of phenolic compounds, terpenoids, and aldehydes, including thymol, carvacrol, eugenol, and cinnamaldehyde. These bioactive molecules disrupt microbial cell membranes, causing leakage of cytoplasmic contents, collapse of membrane potential, and inhibition of essential enzymatic processes [70]. For example, thymol and carvacrol, present in thyme and oregano oils, integrate into lipid bilayers of fungal hyphae, leading to structural disintegration and cell death. In grain storage trials, vapor phase application of thyme and oregano oil significantly reduced growth of Aspergillus *flavus, Fusarium graminearum,* and *Penicillium verrucosum,* which are among the most damaging spoilage fungi in cereals [69]. Clove oil, rich in eugenol, has shown equally strong activity, with minimal microbial regrowth even after prolonged exposure periods.

This antimicrobial action is not limited to fungi; several bacterial contaminants of stored grains, including *Bacillus cereus* and *Salmonella enterica*, have shown marked susceptibility to EO vapors and surface treatments. Studies by Sci Journals [71] 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 that often work through single biochemical pathways. Multi-target activity reduces the likelihood of microbial resistance development, a critical consideration for long term sustainability.

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Mycotoxin suppression

Beyond preventing microbial growth, certain organic preservatives can directly reduce mycotoxin production, which is a major health concern in cereal storage. Mycotoxins such as aflatoxin B_1 (AFB_1), produced by *A. flavus*, and ochratoxin A (OTA), produced by *A. ochraceus*, are highly toxic, carcinogenic, and resistant to degradation during food processing. EOs achieve mycotoxin suppression partly by inhibiting the growth of toxin producing fungi and partly by interfering with their secondary metabolism pathways. Laboratory trials have demonstrated that thymol, eugenol, and cinnamaldehyde can downregulate key genes involved in aflatoxin biosynthesis, thereby reducing toxin yield even when some fungal growth persists (69). In a 2024 pre-storage wheat trial, application of 1% thyme oil, 1% carnation oil, or 1% malic acid completely inhibited visible fungal growth over 14 days. Increasing concentrations to 8% reduced AFB_1 and AFB_2 levels from ~12 ng/g in untreated samples to non-detectable levels (73). This dual actionfungal growth control and toxin suppression provides an additional layer of food safety not guaranteed by synthetic preservatives, which may control growth but leave residual toxins intact.

Antioxidant and insect repellent properties

Another important aspect of shelf life is the oxidative stability of grains that are kept. Because lipid peroxidation causes rancidity, lipid-rich cereals such as maize and oats can lose their nutritious value, develop off flavours, and become less marketable. Essential oils, especially those derived from oregano, thyme, and rosemary, are abundant in thymol, carvacrol, and rosmarinic acid, which are natural antioxidants. These substances bind pro-oxidant metals, scavenge free radicals, and stop the propagation phase of lipid oxidation (Mohldph encapsulation review, 2024). The red flour beetle (Tribolium castaneum) and the maize weevil (Sitophilus zeamais) are two insects that significantly increase post-harvest losses. Numerous EOs have fumigant, oviposition-deterrent, and insect-repelling properties. In hermetic storage settings, for example, Yu [69] reports that 0.5% clove oil vapours decreased maize weevil infestation rates by more than 70%. This is probably because the vapours have neurotoxic effects on insect olfactory receptors. A preservation agent's total bioefficiency is significantly increased when it combines antibacterial, antioxidant, and insect-repellent properties, offering multimodal protection against a variety of spoiling risks.

Recent Technological Innovations

Nanoencapsulation of essential oils

Essential oils (EOs) are trapped in nanometer-scale carriers consisting of food-grade polymers such chitosan, alginate, or cyclodextrins in a process known as nanoencapsulation, which is one of the most promising advancements in the application of organic preservatives to stored grains. This method tackles the intrinsic drawbacks of EOs, such as their high volatility, oxidation vulnerability, and quick deterioration over time. EOs have a much longer shelf life because their active chemicals are protected from environmental stresses such light, heat, and oxygen by being encapsulated in a protective polymer matrix [72].

Functionally, nanoencapsulation also permits gradual, controlled release of essential oils (EOs), preserving a steady level of antibacterial activity in the grain storage environment. In long term storage circumstances, when a single program must continue to function for several months, this is particularly crucial. Particle size, surface charge, and carrier composition can all be changed to adjust release kinetics. For instance, since chitosan carriers have bactericidal qualities by nature, they can provide an extra layer of antimicrobial activity, while smaller particle sizes increase surface area, improving antimicrobial interaction. Studies using experiments have shown how effective this strategy is. The Mohldph encapsulation review [72] found that after six months of storage, nanoencapsulated thyme oil retained more than 80% of its original antifungal effectiveness, while free (non-encapsulated) oil lost less than 30% of its antifungal activity. Without compromising sensory quality, nanoencapsulated clove oil decreased A. flavus colony forming units by over 4 log cycles Nanoencapsulation also offers the potential to integrate EOs into active packaging materials, where the nanocapsules are embedded in polymer films or coatings that line storage bags or silos. This not only prevents direct contact between oil and grain reducing sensory alterations but also provides a slow and steady release of volatiles that protect the grains from microbial and insect attack. However, scalability and cost remain challenges, as nanoencapsulation requires specialized equipment and careful formulation to maintain food safety standards [69] over 90 days in maize storage testing.

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Rational blend formulations

The creation of sensible blend formulations that combine several essential oils (EOs) or EOs with organic acids to take advantage of synergistic antibacterial actions is another innovation that improves bioefficiency. The idea behind this is that several bioactive substances target different microbial pathways, and when combined, they can provide more robust and wide-ranging protection at lower doses than when used alone. It has been demonstrated, for instance, that a greater variety of storage fungi are inhibited by the combination of thyme oil, which is rich in thymol, and carnation oil, which is rich in eugenol [73]. This synergy allows for reduced dosages, minimizing sensory impacts while still maintaining efficacy. The inclusion of organic acids such as malic acid or potassium sorbate can further enhance antimicrobial action by lowering the pH, creating an unfavorable environment for microbial growth, and potentiating the effects of EOs. Recent storage studies highlight the benefits of such blends. In one wheat preservation trial, a 1% thyme + 1% carnation oil blend reduced fungal contamination to undetectable levels for 60 days, while the same effect required 2% concentration when each was used alone [71]. This synergy allows dosages to be reduced without compromising effectiveness, which lessens sensory effects. Organic acids that lower pH, inhibit microbial growth, and enhance the effects of essential oils, such as potassium sorbate or malic acid, can be utilised to boost antimicrobial activity. Recent storage studies have shown the benefits of these mixes. While each ingredient alone required a 2% concentration to produce the same result, a blend of 1% thyme and 1% carnation oil reduced fungal infection to undetectable levels for 60 days in one wheat preservation experiment [71].

Practical case studies and efficacy data

Well-recorded field and lab experiments provide the best understanding of the bioefficiency of organic preservatives. Yu (69) described a thorough investigation on the use of oils of clove, thyme, and cinnamon in wheat that has been preserved in a controlled setting. A. flavus-inoculated wheat grains were treated with 1%, 4%, and 8% EO solutions in this experiment. The grains were subsequently kept for 60 days at 25°C and 70% relative humidity. Aflatoxin B_1 levels were lowered to below the detection limit of 0.5 ng/g due to the 8% treatments, which also totally stopped visible fungus growth. Another study [71] looked at the vapor-phase action of six essential oils (EOs) against naturally contaminated maize. These included cinnamon, clove, eugenol, orange terpenes, oregano, and thyme. Oregano and thyme oils reduced fungal colony counts by 75 to 85% during 30 days of hermetic storage, whereas cinnamon and clove oils reduced them by over 90%. These decreases showed consistency between replicates, suggesting that the impact was reliable. Pre-storage studies on wheat [73] showed that EOs and organic acids worked well together. While the same EO alone took 28 days to completely suppress A. flavus, a 1% thyme oil + 1% malic acid therapy removed detectable A. flavus in 14 days. Additionally, the combination maintained sensory qualities better than high-concentration single EOs, indicating a useful benefit for customer acceptance. Regarding insect control, Yu [69] employed hermetically sealed maize storage bins infested with Sitophilus zeamais to evaluate clove oil vapour. While 1% achieved over 90% suppression without the use of chemical insecticides, a 0.5% dose of clove oil reduced insect emergence by 72% when compared to untreated controls. All of these case studies show that organic preservatives are a good substitute for synthetic compounds since they can provide reliable, multifaceted protection in both lab-scale and real-world storage situations.

Limitations and challenges and future directions

Despite the significant potential of organic preservatives, a number of obstacles prevent their widespread use. Plant species, cultivar, geographic origin, harvest season, and extraction technique are some of the variables that can drastically change the amounts of important bioactives in essential oils (EOs), raising serious concerns about chemical composition variability [70]. Regulatory approval and market acceptance depend on quality control and standardisation, both of which are made more difficult by this diversity. The influence on the senses is another drawback. Strong scents from many EOs may give stored grains unwanted flavours or odours at high enough concentrations.

In markets where neutral taste characteristics are sought, this could be an issue. This can be lessened by sensible mixing and encapsulation, but total sensory effect removal is difficult. In poor nations, cost and scalability continue to be obstacles. Although EOs can be obtained locally in many places, certain tools and knowledge are needed for the extraction, encapsulation, and blending procedures. The capital-intensive nature of nanoencapsulation in particular may impede

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smallholder farmers' uptake in the absence of subsidies or cooperative investment. The laws governing organic preservatives are constantly being developed. Application rates, residue restrictions, and labelling requirements differ significantly between jurisdictions, even though many EOs are permitted for limited use in the EU and categorised as GRAS in the US. Because nanomaterials in food systems are novel, nanoformulations are subject to further examination [69].

Grain handlers and farmers lack understanding about proper dosages, administration techniques, and integration with other post-harvest procedures. Even the most effective preservative may not work as intended in practical situations if the user is not properly trained. It is necessary to address a number of research and development priorities in order to optimise the potential of organic preservatives in cereal grain preservation. It may be possible to minimise variability and guarantee constant bioefficacy by standardising the composition of EO by chemotyping and controlled culture. It is important to incorporate analytical instruments like high-performance liquid chromatography (HPLC) and GC-MS into quality control procedures.

To confirm laboratory results and identify the best formulas for certain areas and grain kinds, extensive field testing in a variety of climatic zones is necessary. Along with microbial and toxin reduction, these trials should evaluate the effects of storage for at least six months on nutritional value, germination rates, and sensory quality. Strategies to cut costs are also essential. This could entail creating inexpensive encapsulation methods with locally accessible materials or establishing cooperative processing facilities that give smallholder farmers access to cutting-edge formulations at reasonable costs.

Reliance on refrigeration or artificial fumigation may be lessened while the durability of preservation effects is increased through integration with low-tech hermetic storage systems. For instance, EO-infused sachets or hermetic bag liners could provide controlled release protection without requiring a significant investment in infrastructure. For organically preserved grains to be traded across borders and approval procedures to be streamlined, regulatory harmonisation is required. Establishing science-based limitations and labelling requirements will necessitate cooperation between food safety agencies, researchers, and industry players. Last but not least, increasing capacity via extension and farmer education programs will be essential. Farmer-to-farmer knowledge sharing, training initiatives, and demonstration projects can hasten uptake and guarantee proper use of the technologies.

More and more scientific research is proving that organic preservatives are bioefficient in preserving wheat grains that have been preserved. Insect infestation, mycotoxin contamination, oxidative rancidity, and microbiological spoiling can all be prevented with the help of essential oils and organic acids. Long-term grain preservation is becoming more and more feasible thanks to recent advancements like nanoencapsulation and rational blend composition, which are overcoming the conventional constraints of volatility, instability, and sensory impact.

According to recent case studies, when prepared and used appropriately, organic preservatives can function just as well as or better than synthetic ones. In addition, they offer further benefits in terms of environmental safety, consumer acceptance, and biodegradability. However, successful mass adoption will need addressing compositional heterogeneity, financial limits, regulatory complexity, and knowledge gaps in application practices. Integrating organic preservatives into grain storage systems provides a sustainable, scientifically validated solution to the issues facing global food security, especially in underdeveloped countries where post-harvest losses are most noticeable. Coordinated research, policy backing, and capacity building may make these natural agents the foundation of future-proof grain preservation methods.

Natural preservatives and their mechanisms

Antioxidant, antifungal, and antibacterial properties have been demonstrated for the monocyclic terpene D-limonene. Its hydrophobic properties allow it to interact with bacteria' membranes, increasing permeability, allowing cellular contents to leak out, and ultimately leading to microbial cell death [76]. Additionally, D-limonene enhances the shelf life of foods containing lipids by scavenging free radicals and inhibiting lipid peroxidation [77]. However, the main way that ethanol acts as an antibiotic is by denaturing proteins, breaking down lipids in cell membranes, and disrupting the metabolism of bacteria. Due to its broad-spectrum activity, ethanol effectively combats common food deteriorating agents such as bacteria, yeast, and mould.

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Synergistic effects of combined preservatives

According to recent research, combining natural preservatives can have synergistic effects, in which the combined antioxidant or antibacterial activity is higher than the total of the effects of the separate preservatives [74]. Ethanol and D-limonene together have a greater ability to promote intracellular leakage and membrane breakdown in microorganisms than either substance alone. Because D-limonene is lipophilic, it can make microbial membranes more permeable, which makes it possible for ethanol to enter more effectively and interfere with cellular metabolism. Additionally, ethanol and D-limonene can both inhibit microbial development and offer antioxidant protection, resulting in a dual preservation mechanism. Lower amounts of each component may be possible thanks to this synergy, which would preserve the food product's preservation effectiveness while minimising sensory changes.

Application in food systems

Beverages, dairy products, and baked goods are just a few of the food systems where D-limonene and ethanol combinations may find use. D-limonene's inherent scent, for example, can enhance citrus-flavored drinks, and when used in moderation, ethanol controls microbes without compromising flavour. The volatility of ethanol also permits quick evaporation during baking, allowing D-limonene to retain its antifungal and antioxidant properties in baked goods. Because these combinations can affect the preservative efficiency, their composition necessitates thorough optimisation, taking into account variables including pH, water activity, temperature, and interactions between the food matrix [75]. Furthermore, encapsulation methods like nanoencapsulation or microemulsions may improve these natural chemicals' stability and controlled release, enhancing their potential for synergy.

Safety and regulatory considerations

The toxicity, allergenicity, and sensory impact of natural preservative mixes should be evaluated even though they are generally regarded as safe (GRAS). Although D-limonene is generally regarded as safe for use in cooking, high concentrations may cause interactions with other ingredients or result in odd flavours (76). Ethanol must be carefully controlled in concentration to meet food safety regulations even though it is frequently used in food and beverages. In order to ensure consumer safety and commercial acceptance, each new formulation should adhere to the permissible levels of natural preservatives set by regulatory agencies such as the FDA and EFSA (77). Research into developing new organic preservatives should focus on figuring out how they work in different food matrices and maximising their synergistic combinations. Through high throughput screening of mixes of food-grade solvents and essential oil components, effective preservative blends can be identified. Moreover, nanotechnology-assisted encapsulation and regulated release may lengthen shelf life while minimising sensory changes. Eventually, these formulations may replace artificial preservatives, meeting consumer needs for natural, safe methods of food preservation while preserving food quality and reliability.

CONCLUSION AND RECOMMENDATION

Conclusion

Interest in natural substitutes has surged as a result of growing worries about the possible negative effects synthetic preservatives may have on human health and the environment. Consumers are increasingly choosing natural ingredients over synthetic ones and favouring clean-label food items. The use of entomological and biotechnological methods can efficiently address challenges in the management of insects and pests. It is also possible to optimise the storage environment using contemporary computational fluid dynamics (CFD) technologies. In order to enhance material and structural design, the finite element method (FEM) can be used to analyse the impacts of stress during grain filling and emptying. Grain flow characteristics and design modifications can be precisely controlled by incorporating precise electronic sensor data into CFD and FEM models. This reduces postharvest losses and maintains grain quality.

Recommendation

Interest in organic substitutes has grown as a result of the drawbacks of traditional chemical preservatives, such as their toxicity and negative effects on the environment. Spray drying, nanoemulsions, and liposomal systems are examples of nanoencapsulation techniques that have been investigated to enhance the stability, bioavailability, and controlled release of bioactives. It has been demonstrated that application in grains can effectively lower the microbial load and increase shelf life. Nevertheless, issues like irregular release, food matrix

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interaction, sensory interference, and high production costs were noted. Large-scale use is also constrained by safety and regulatory issues. Chitosan, starch, and alginate are examples of encapsulation materials that have been extensively researched. The assessment also emphasised how limited scalability and market preparedness pose challenges to commercialisation. Nanoencapsulation is still a promising area in sustainable grain preservation in spite of these obstacles.

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