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Bio-based preservatives: A natural alternative to synthetic additives

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Abstract

In this study, the use of bio based preservatives, as a more sustainable, and health conscious alternative to synthetic additives in food preservation is investigated. The history of historical development of these natural preservatives is covered, identifying major innovations that take advantage of the antimicrobial and antioxidant properties of plant and microbial derived compounds. Some core theories and models are discussed and illustrated, which are effective in enhancing shelf life and food safety. The work reveals critical barriers to wide scale use including high costs, scalability limitations, and stringent regulatory approval processes. Barriers to the mass production of silica aerogel blanket materials are evaluated and strategies proposed to overcome these barriers are evaluated, including collaboration with regulatory bodies, the application of nanotechnology, and cost reduction techniques including optimization to raw material sourcing and leveraging of economies of scale. Synthetic preservatives are compared with tradeoffs between performance, safety, and cost, demonstrating the advantage of bio-based solutions for those applications where health and environmental considerations are important. Finally, the study suggests future research directions related to ways to increase efficacy through technological innovations, reducing cost, and making the regulatory framework more streamlined. This study provides actionable insights to food manufacturers, regulators, and consumers towards a transition to more sustainable preservation systems. Adoption of bio-based preservatives has great public health, industry usage and environmental sustainability implications.

Keywords: Bio-based preservatives; Synthetic preservatives; Food preservation; Antimicrobial properties; Antioxidant activity; Regulatory challenges; Cost-effectiveness

1. Introduction

1.1. Overview of Bio-based Preservatives

Preservatives are used to extend the shelf life of a food by preventing spoilage and inhibiting the growth of harmful microorganisms in foods and may be bio-based or of natural origin (from a plant, animal or microorganism). Bio based preservatives are safer and more sustainable than synthetic preservatives which are chemically engineered often and may be dangerous. Yet, rising consumer demand for natural, organic and minimally processed products, coupled with safety concerns around the possible adverse health effects of synthetic chemicals, has created the perfect market opportunity for these preservatives in the food industry. According to Vestal, although the use of natural preservatives is not a new practice, historically they've been used during ancient civilizations to form methods to preserve food. More recently, the appearance of synthetic additives in the 20th century caused a turn to new food preservation practices. Yet, the upsurge of awareness of the risks that synthetic chemicals can pose to health (allergens and carcinogens among them) has rekindled interest in bio based preservatives. This is now recognized that there are plenty of natural substances such as essential oils, plant extracts as well as fermentation by products that can prolong food shelf life without compromising its safety and nutritional value [1]. Clean label products, free from artificial ingredients, is increasing consumer demand, and bio-based preservatives are a promising solution to fill this need. Consumer

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preference and evolving regulatory framework favoring safer, more sustainable alternatives to synthetic chemicals pushes this shift [2]. Thus, the development and use of bio based preservatives will be a potential key solution in upcoming food preservation.

Few primary reasons for this are health concerns, environmental sustainably and obviously the changed consumer preferences that demand natural alternatives in food preservation. Awareness about the potential risks of the synthetic preservatives can be rising, and the consumers are looking for food products free from artificial components. Natural preservatives from plant, or microbial, sources not only provide a safer alternative which lessens the extent of exposure to harmful chemicals like preservatives possibly contributing to food allergies or potentially health concerns in the long run, they also present other benefits [3]. Trends in turned ingredients, caused by increasing health concerns and the widening knowledge about the side effects of synthetic additives, figure in this area as well. Natural preservatives are believed to be less harmful to health and better suited to a healthier lifestyle. Also, these alternatives are typically less processed than conventional methods so that they maintain the nutritional integrity of food, which appeases health conscious consumers [4]. Environment is also played as a key factor in favor of more ecofriendly preservatives. Usually, the natural preservatives are biodegradable, and have a lower impact on the environment, compared to the synthetic ones, which could compromise pollution and waste. Globally, this compares with the increasing consumer awareness about sustainability and environmental footprint of food production [5], and economically, it is favored by regulations in many regions that drive the use of safer and more sustainable substances in food and packaging. Because natural preservatives appeal to consumers, fast food manufacturers are meeting this demand by adjusting product formulations and adapting to these regulation changes and, therefore, are developing a competitive market with bio based solutions.

1.2. Objectives and Scope of the Study

The aim of this study is to evaluate the possibility of bio-based preservatives as viable, sustainable, preservatives to synthetic preservatives in food preservation. The main aim of this article is to evaluate the safety, effectiveness and consumer acceptance of natural preservation approaches based on the biological systems, like plants, microbe or enzymes. In addition, it will assess the technology advancements and regulatory frameworks that determine the adoption of bio based preservatives in food industry. This study will address several key research questions: Is there any advantages and limitation in bio based preservatives compared to synthetic chemicals? What effects do bio based alternatives have on food safety, quality and shelf life? What are the problems faced by food manufacturers in making these preservatives part of their products? Moreover, the article evaluates the environmental merits of bio based preservatives and their part in the sustenance of reasonable food production procedures. This research encompasses scientific fundamentals of bio-based preservatives, their applications in the present food industry and regulations. This study analyses these areas in the hope that the contribution will help disentangle these challenges and to contribute to a better understanding of how bio-based preservatives could address the increasing demand from consumers for natural, safe and environment friendly food preserving solutions.

1.3. Significance of the Study

This is an important study since food preservation encompasses critical incongruences and as the consumer demand for bio based replacement for synthetic preservatives increase. However, an ongoing growing concern over food industry's chemical additives' health risk is forcing the industry to explore safer and yet milder preservation methods. In addressing the need for a better understanding of bio based preservatives and their effectiveness this research offers worthwhile information on their possible role as a substitute or partial solution to synthetic chemical preservatives. Bio-based preservatives offer the opportunity to decrease the risk of reactions from synthetic additives, for example allergies and long term health problems, from a public health perspective. Moreover, using them can also be part of more sustainable food systems, by decreasing the environmental footprint of chemical production and disposal. The results of this study may inspire the industry as a whole to adopt bio based solutions, delivering healthier, more transparent products to the consumer. Additionally, the study also assesses the cost effectiveness of bio based preservatives from an economic perspective while leveraging data from the study results to advise the food industry on adoptability and implementation of bio based preservatives in their manufacturing processes without impacting quality and costs of the end products. In doing so, this study contributes to the growing trend for more sustainable and consumer friendly means of food preservation.

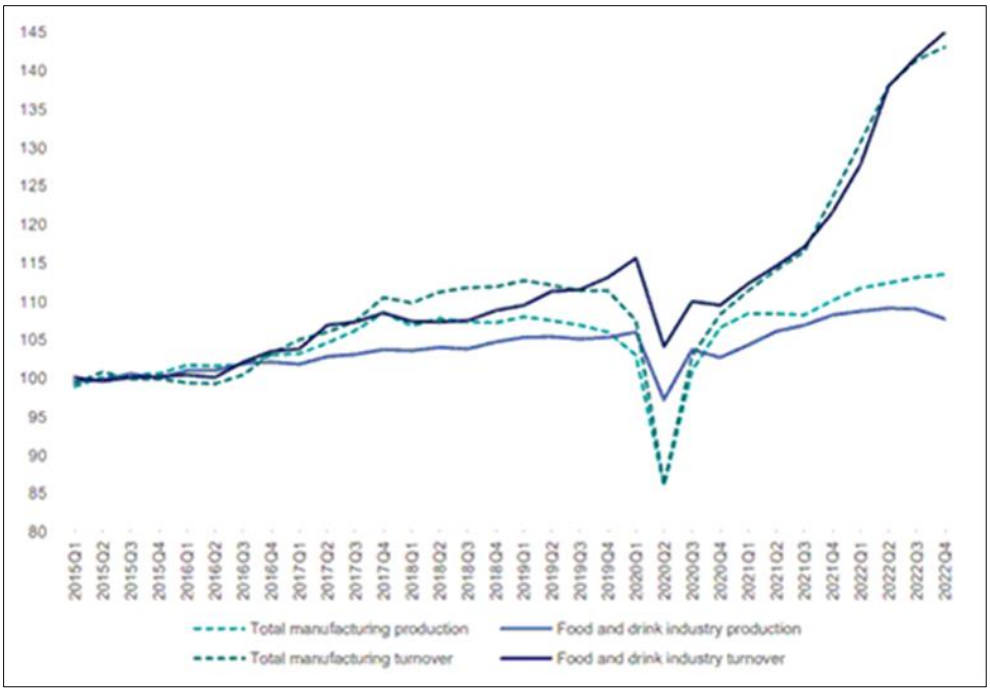

Figure 1 Demand for natural food additives in Europe

2. Literature Review

2.1. Historical Development of Bio-based Preservatives

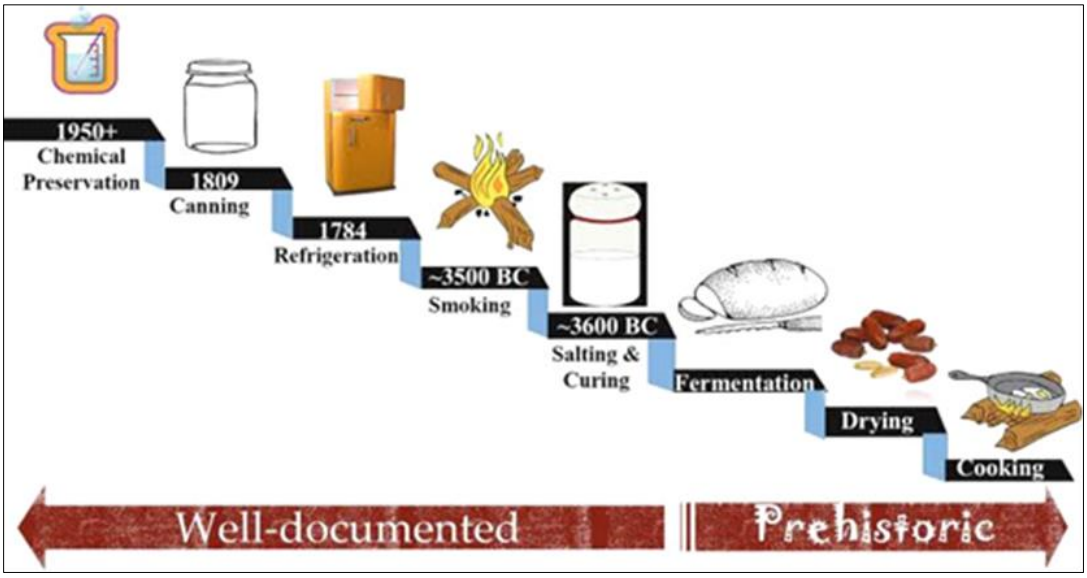

Figure 2 History of food preservation

Going back to ancient times when humans were looking for ways to preserve food and prevent its spoilage, we have history of bio based preservatives. Methods which were early, like smoking, salting and fermentation all were natural process past which makes used substances like salt, vinegar and herbs to stop microbial growth and to keep up food for longer duration. These methods also established the use of bio based substances in food preservation, indicating an understanding of these substances to keep food safe enough to eat over increasingly long periods of time, without the addition of artificial additives. Although widespread industrialization of food production in the twentieth century led to a focus on the use of synthetic preservatives, including sodium benzoate, nitrates and artificial antioxidants. The cost effectiveness and the shelf life of these chemicals, favored them. However, doubts as to the risks posed by these all things

synthetic, ranging from allergies to toxicity and to their connection with one chronic disease after another, started to pose themselves. Finding safer, more sustainable alternatives to these synthetic preservatives sparked a growing interest in bio-based solutions which started to take off again. Over the course of the last few decades, research into bio based preservatives has improved, with discoveries of extracting natural compounds from plant based sources, essential oils and even microbial fermentation. Plant polyphenols, organic acids and antimicrobial peptides are bio-based substances, demonstrated herein to have preservative properties, which provide safer and more natural means for food preservation. With consumer demand for leaner, more natural products on the rise, the food industry has followed suit, opting more and more for these alternatives as a replacement for synthetic chemicals [7][8]. Currently, basic research works are being carried on in the field of food technology areas, focused on the development and enhancement of the bio based preservatives, because today they are investigated as a central focus in the area of food technology. This change is part of a larger tendency towards healthier and more sustainable food systems, spurred on by either consumer preferences or regulatory measures [9].

2.2. Core Theories and Models Related to Bio-based Preservatives

Several scientific theories explain how bio–based preservatives are effective in extension of shelf life and maintaining food quality, which make the use of bio–based preservatives in food justified. Of these two, one theory is the antimicrobial theory with regards that certain natural compounds can inhibit the growth of microorganism, which caused the food spoilage. The disruption of microbial cell membranes, interference with metabolic processes and prevention of the growth of harmful bacteria, molds and yeasts is also recognized as known contributions of essential oils, phenolic compounds and organic acids, all plant derived antimicrobial agents. Plant based preservatives represent a valuable alternative to synthetic preservatives owing to these antimicrobial properties that prevent spoilage and food borne illnesses [1]. An additional important theory which theorizes that bio based preservatives are able to help combat oxidative stress in food is the antioxidant model. Food, but especially fatty foods, can go rancid; have their color and nutrients changed; and are oxidized. There are natural antioxidants that occur naturally in plants, products like polyphenols, flavonoids and they have vitamin C, and what they do is neutralize free radicals and slow the oxidative damage. The ability to ensure sensory and nutritional quality of food plays a major role in that increasing interest in bio-based preservatives, which are safer and more environmentally friendly option than synthetic chemicals [9]. When applied to contemporary research and practical applications, these theories make a sound science basis for bio-based preservatives. As a result, understanding of the antimicrobial and antioxidant properties of natural ingredients can help guide the development of innovative, sustainable, preservation approaches. These theories have continued to guide the ongoing exploration of bio based preservatives and broader potential in food safety and sustainability, as the demand for natural alternative to synthetic additives increases [10].

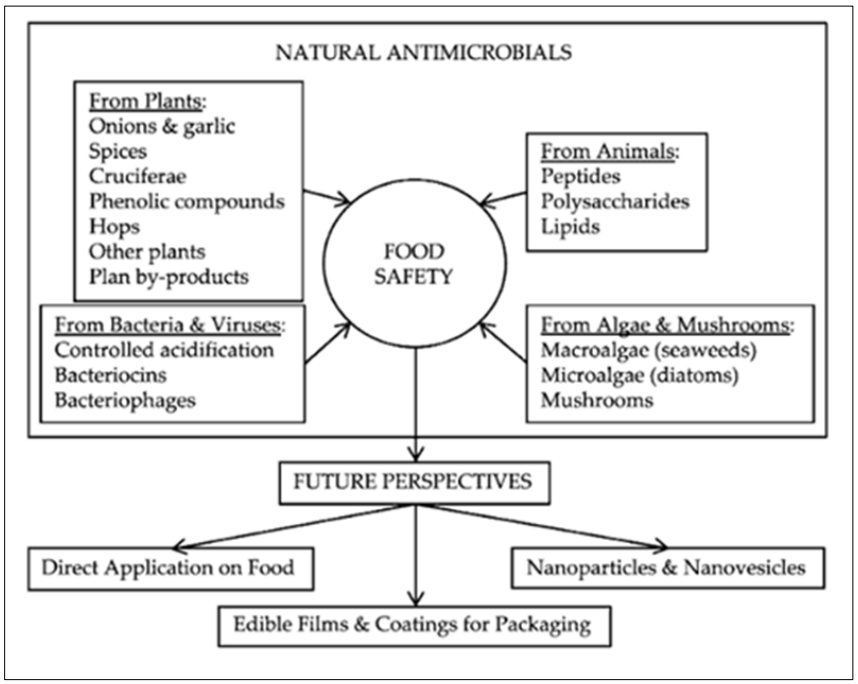

Figure 3 Overview of industrial microbiology applications in food processing

2.3. Previous Research and Findings

A growing interest in the use of bio-based preservatives as viable alternative to synthetic chemicals in food preservation has been the subject of a number of recent studies. Antimicrobial properties of plant derived preservatives, essential oils, plant extracts, and other bioactive compounds are one critical research area. An analysis of bio preservation methods revealed that natural preservatives can be used to prevent microbial growth and prolong the life of numerous foods [10]. The methods used in these studies are usually a combination of in vitro testing, microbiological assays and sensory evaluations to evaluate the inhibition of spoilage micro-organisms by natural substances. Shankar and colleagues (2017) studied the use of turmeric extract as a bio-preservative of tomatoes. The researchers found their research showed that the antimicrobial properties of turmeric could considerably slow the growth of spoilage bacteria and help prolong the shelf life of tomatoes. Using microbial cultures and chemical analyses, its effectiveness in turmeric extract in replacing chemical preservatives including sodium benzoate (a preservative used in tomatoes) was researched [12], and also a strong influential study looked at the bio-preservative potential of other plant based substances such as cinnamon, and clove oils.

Both oils had strong antimicrobial activity against a variety of bacteria and fungi, including pathogens E. coli and Salmonella, researchers determined. According to the study, cinnamon and clove oils could actually replace synthetic preservatives, like sodium nitrite, in meat products as safer and more natural food preservation choice [11]. The studies demonstrate the great strides being made to replace synthetic preservatives with natural equivalents. The variety of bio-preservatives derived from plants, including turmeric, cinnamon and clove oils, are emphasized, because they both eliminate the requirement for synthetic chemicals and come with benefits, such as antioxidant activity. The methodologies from these studies, which span from microbiological testing to chemical analyses, have been shown to be sufficiently robust for determining the feasibility of naturally derived preservatives for use in real world applications in food preservation. Overall, the body of research on bio based preservatives portends both the improvement of food safety as well as the realization of longer shelf life and sustainable, health conscious alternatives to synthetic chemicals. The more evidence is building in order to support the transition to more natural preservation methods and pave the way for industry wide food safety practice changes.

2.4. Research Gaps and Emerging Issues

Bio-based preservatives have a very exciting potential, but several research gaps and emerging challenges stand in the way for their widespread use in food preservation. A huge gap is scaling up bio based preservative production. While laboratory-scale studies have shown these methods to be effective, scaling these methods to produce them commercially is a challenge. For example, the extraction and processing of plant based compounds to a scale necessary for use in place of synthetic preservatives can be expensive and energy intensive and be problematic from an economic perspective with respect to feasibility as an alternative to synthetic preservatives [13]. To compete in a market of cheaper, synthetic chemicals, this issue needs to be addressed. Furthermore, cost is still the biggest hurdle. The production of bio based preservatives, including plant extracts, essential oils, requires complex processes leading to production costs typically higher than that of conventional preservatives. However, this can discourage adoption by food producers who are mainly in the low margin sectors such as packaged foods and beverages [14]. These barriers can be reduced by research into more efficient extraction methods as well as cost effective production techniques. One challenge is that the bio-based preservatives are not effective in all food products.

Although researches prove that some natural preservatives can work in certain occasions, their effectiveness still requires food type, or storage condition, or microbial contamination coming in play to complete the picture [14]. Further research is required to best formulate and apply these preservatives so that performance is consistent from one food to the next. Future research avenues include the improvement of scalability and cost effectiveness of bio based preservatives, and the investigation of new methods of use, such as nanotechnology to increase preservation efficacy and food shelf life. Furthermore, the development of new bio-based preservative formulations (perhaps via fermentation process or biocatalysts) may provide new ways to merge bio-based preservatives into mainstream practice in food preservation [15]. Solving these research gaps will be critical in making the transition to more sustainable and health conscious food preservation practices.

3. Key Challenges and Issues in Bio-based Preservatives

3.1. Regulatory and Safety Challenges

Integration of bio based preservatives in the food industry has been beset by regulatory and safety challenges. It is mainly due to the fact that thorough safety evaluation and navigating through the lengthy, cumbersome regulatory systems which require lengthy times (including approval from U.S. Food and Drug Administration (FDA) and European

Food Safety Authority (EFSA)) pose these challenges. As one of the major regulatory hurdles bio-based preservatives encounter, there exist no established guidance for approval and use of bio-based preservatives. Synthetic preservatives have decades of use and well known safety data, bio-based preservatives, including natural derived plant extracts, are often new substances. And so they need a good deal of testing before they can be introduced broadly into food products. Bio based preservatives are required by the FDA as well as the EFSA to undergo extensive toxicological testing to ensure their safety. Studies on the preservative's capacity to induce allergic responses in addition to toxicity levels and long term health effects, should the chemical be taken in on a consistent basis over time [15]. However, due to the lack of comprehensive data for all bio-based compounds, such materials have encountered major barriers to their acceptance and use by the food industry.

The other major problem is its safety concerns. Although bio based preservatives are thought to be more natural and less dangerous than synthetic, they can have negative effects on populations susceptible to their effects. Also, some plant based preservatives can cause allergy, especially for people who have allergy to some of the plant contents. Therefore, rigorous allergenicity testing to demonstrate that the compounds so derived are not likely to be significant threat to public health is essential. Among other things, as with any new preservative within food, manufacturers must show that their product effectively prevents microbial growth, without sacrificing the safety or nutritional value of the food. Demanding studies are required on mechanism of action of bio based preservatives e.g. antimicrobial or antioxidant properties as well as their interactions with food matrices and under different storage environments [15]. Bio based preservatives are, however, chronically difficult to standardize in testing protocols being complex in nature. They also tend to have more well defined structures and properties that we can more easily test and evaluate. But bio-based preservatives are composed of a large variety of complex materials and the variability in composition of, not only bio-based preservatives, but bio based materials generally, due to plant type, extraction method and environmental effects, can complicate safety assessments. The process of getting food additives approved is a long one and sets high thresholds for being approved, for example from the FDA and EFSA. The time and financial investment needed from manufacturers to determine the safety and efficacy of each bio based compound also causes substantial delay.

But the complex nature of evaluating natural substances also makes the regulatory approval process for bio based preservatives more time consuming than that for synthetic preservatives. Bio based preservatives must undergo extensive testing and approval of acceptable usage levels without risk to human health or the environment, and regulatory agencies must check that this is so. However, synthetic chemicals are usually approved and implemented much more quickly for this kind use than bio-based preservatives, largely because there is a long history of using synthetic chemicals within food preservation [16], which can result in an unnecessary delay in the commercialization of promising bio-based preservatives. Yet, growing interest in natural preservatives exists to satisfy consumer demand for clean label products and concerns related to safety of synthetic additives used in foods. This leads regulatory bodies to recognize the necessity for clearer rules on bio based bio preservatives, as this process could lead to a quicker approval process as well. With this shift, there is potential to further accept the use of bio based preservatives into the food industry, as a more sustainable and health conscious alternative to the use of synthetic chemicals.

3.2. Effectiveness in Diverse Applications

Across different industries, like food, cosmetics, and pharmaceuticals, the effectiveness of bio based preservatives have already been explored. These preservatives are usually from a natural origin, such as plant extracts and essential oils as well as microbial metabolites, which have its own benefits like antimicrobial, antioxidant and antifungal. But their success, or their challenges, depend on the industry and the particular application.

Promising new bio based preservatives have been developed in the food industry. For instance, plant based preservatives including those made from rosemary, oregano and thyme have antimicrobial as well as antioxidant properties. There is evidence to show that these bio based preservatives greatly increase shelf life of dairy, bakery and meat products and increase food safety as they inhibit the growth of harmful microbes [10]. The principal case study involved turmeric, a well-known plant extract that was shown to be an effective natural preservative to prevent microbial spoilage in tomatoes. Undoubtedly, its antimicrobial action and antioxidant properties were good to inhibit food spoilage, therefore it can be a proper alternative for synthetic preservatives [10]. The main challenge in food applications, however, is the unpredictable potency of bio-based preservatives, which can depend on multiple parameters such as the type of plant source, extraction method and storage conditions.

As consumers demand clean and natural products, bio based preservatives are being brought into cosmetics to fit in with formulation formulations. As antimicrobial and antifungal preservatives, we use essential oils like lavender and tea tree oils. These natural alternatives less risk to irritate or cause allergic reactions as opposed to synthetic chemicals as parabens. However, whereas these materials have potential for use in cosmetic products, issues such as skin

sensitivity or necessity of high concentrations to assure effectiveness limit use [18]. Regulatory hurdles also persist in the cosmetic industry for the adoption of bio based preservatives, compared to their synthetic counterparts. Bio based preservatives are used in pharmaceuticals where the stability of drugs and their integrity, especially in topical applications is maintained. Honey and aloevera extract preservatives have naturally acted as antifungals and antibacterials that have inhibited the contamination of topical ointments and creams. But this sector also faces the challenges of ensuring that the bio based preservatives do not change the efficacy of drug or cause unintended interactions with active pharmaceutical ingredients. Currently, [17] a major obstacle to the acceptance of bio-based preservatives is the requirement for extensive testing in accordance with stringent regulatory standards applied to pharmaceutical products. Aside from the use of natural products in food and cosmetics, wood coating is a good example of a bio based preservatives where natural products are used to protect from degradation. Protective coatings preventing the decay of wooden surfaces have been made from bio based plant oil derived preservatives including linseed oil. Even though these natural preservatives have been proven effective as a non-toxic environmentally friendly alternative to synthetic chemicals they face some problems with their durability and longevity when it is subjected to harsh environmental conditions [18]. Consequently, bio-based preservatives have proven promising in various fields, but these preservatives present challenges in terms of consistency, regulatory approval and effectiveness. However, barriers still remain to the widespread adoption of bio-based preservatives as sustainable alternatives to synthetic chemicals, such as cost issues and challenges in developing a variety of preservative products that can span the wide range of structures and properties of bio-based natural compounds.

3.3. Cost and Scalability

However, the adoption of bio based preservatives is wide spread, but this comes with large cost and scalability challenges. The problems with these preservatives arise due to the production costs and the availability of raw materials, as well as the economic viability of large- scale application of such preservatives across different industries. Cost became one of the main problems that arise due to high bio-based preservatives production cost. In contrast to the known chemical manufacturing processes used for synthetic preservatives, the manufacturing processes of bio based preservatives are more likely to involve solvent extraction, distillation and/or fermentation. However, the processes tend to be both labor intensive and those requiring use of sophisticated technology, hence the production costs are high [19]. Furthermore, plant derived bio based preservatives are susceptible to seasonal constraints regarding the availability of raw material. For one, prices for the essential oils found in, say rosemary and thyme, might be expensive because these plants only grow in limited geographical regions and so the oil is also expensive to extract. Roughly, this leads to fluctuations in supply that also disrupts the stability in pricing of bio based preservatives [20]. Moreover, the scale of bio based preservatives is an important concern. These preservatives have the potential to serve well in small scale applications but at scale they require massive infrastructure investment including large fermentation tanks, and extraction facilities. The conversion of bio based compounds into preservatives too requires lot of research and development investment to make the production methods as optimized and to produce a consistently high product quality. In other cases, production scale up might also need new supply chains to support a reliable and cost effective flow of raw materials [21]. In addition, achieving a consistent product from batch to batch can be difficult due to inconsistent quality of bio-based preservatives as a function of the plant species, growing conditions, and harvest timing.

Finally, competition from well-established synthetic preservatives has an effect on the economic viability of bio-based preservatives for their use in large scale industrial application. Now found in the global supply chains, synthetic preservatives like sodium benzoate and potassium sorbate have economies of scale and are perfectly fused to global supply chains. They are also cheaper and more readily available than their bio based counterparts. At present, the higher production costs and the likely volatility of raw materials for bio based preservatives [20] make them an unattractive proposition for industries interested in minimizing costs.

Even faced with these challenges, there continues to be a push to increase the cost-effectiveness and scalability of bio based preservatives. The development of engineered microorganisms that can produce bio based preservatives to enhance efficiency, is an example of advances in biotechnology that should be considered. In particular, it has been suggested that the biosynthetic capabilities of a genetically modified, not necessarily pathogenic, bacteria or fungi, for the large scale production of antimicrobial compounds, e.g. lactic acid or natamycin may reduce production costs [21]. Moreover, investigation into developing bio-based preservatives from abundant and renewable feedstocks including agricultural byproducts could in the future yield low cost and scalable alternatives. Finally, the conclusion is that bio-based preservatives represent a major opportunity to improve food safety and sustainability, but the cost and scalability challenge will continue to prohibit their use in practice. Further research and technological improvements will be needed to overcome these challenges and more economically make bio-based preservatives scalable for global industries.

4. Solutions and Mitigation Strategies

4.1. Enhancing Efficacy through Innovation

Ensuring efficacy and stability in applications ranging from food to medicines, requires innovative approaches to increasing the efficacy of bio-based preservatives. Blending of natural compounds, nanotechnology incorporation and fermentation processes represent among the most promising strategies. These innovations are assisting to compensate for the natural limitations of bio based preservatives, which are less stable and have a narrower range of activity than synthetic preservatives. One of the simplest but most effective ways of increasing the performance of bio based preservatives is to blend different natural compounds. Combining compounds with complementary mechanisms of action, for example antimicrobial and antioxidant, improves efficacy of the mixture of preservatives. For instance, essential oils, e.g. thyme and rosemary, combined with other bioactive plant extracts enhanced their antimicrobial activity protecting wider from spoilage microorganisms [15]. Such a synergistic effect can be used to prolong shelf life of food products without degrading the safety and quality of food.

Property	Performance Requirement
Antimicrobial activity	Active against bacteria (Gram +ve/Gram –ve), molds, yeasts and fungi at low inclusion levels
Aqueous solubility	Solubility exceeds minimum inhibitory concentration (MIC) over anticipated product pH range and throughout product shelf life
Partitioning behavior	Sufficient preservative remains in the continuous phase (aqueous) in multi-phase products, e.g. suspensions, creams, ointments, etc., to evince the requisite antimicrobial effect throughout products shelf life
Adsorption behavior	Does not physically interact with other formulation constituents (particularly those with large surface areas) or with the container/closure
Stability	Chemically and physically stable during manufacture, over its in use shelf-life and at the end of its product shelf-life
Compatibility	Does not chemically react or reacts minimally with other formulation constituents, including the container/ closure
Organoleptic properties	Odor and taste acceptable for orally, intranasal or pulmonary administered products (the latter two routes of administration can have a significant swallowed fraction)
Non-irritant	Non-irritant at typical concentrations used in the product, especially for of sensitive mucosal membranes, e.g. eye, nose, etc.

Figure 4 Choosing a preservative system in antimicrobial formulations

Bio based preservatives have also found to be discreetly revolutionized with the help of nanotechnology and their efficacy has also been improved. The addition of bioactive compounds to nanoparticles increases their stability and enhances bioavailability. The amount of surface area increases, and more effective interaction with microbial cells occurs. This new technology provides for the controlled release of preservative substances, increasing their persistence with time and obtaining a prolonged effect. Also, as incorporated into nanoparticles, sensitive bioactive compounds are protected from degradation by factors such as oxidation or volatilization; thus reducing the potency of natural preservatives [22]. Encapsulating essential oils or plant extracts into nanoparticles assures targeted, effective delivery of the active ingredients, and provides both stability and efficiency in multiple applications. Fermentation, an age-old process with food preservation history, has also gained renewed interest as a way to boost bio-based preservative production and efficacy. Fermentation for the production of natural preservatives, for example, organic acids, peptides and bacteriocins, is picking up speed. As an example, antimicrobial peptides that exert an antimicrobial effect can be produced in fermentation by lactic acid bacteria (LAB) as natural preservatives. The preservative qualities of these fermentation derived products are attractive, mainly due to their GRAS status with regulatory authorities, and high level of consumer acceptance. Moreover, the byproducts themselves can be formed during the fermentation process, which can produce novel preservative compounds with improved stability, and antimicrobial activity that will mitigate the problem of short shelf life present in bio-based alternatives [16]. Summing up, continuous innovation of blending

natural compounds, applying nanotechnologies, and optimization of fermentation process promotes to increase efficacy of bio based preservatives. By addressing traditional challenges with these innovations that bio-based alternatives typically face, including stability, cost and efficacy, these innovations are helping prepare the way for broader use in food preservation and beyond. Research in these areas is progressing and, as such, bio based preservatives will likely become more effective, stable and economically viable for a sustainable and health conscious future.

4.2. Addressing Regulatory and Safety Barriers

To promote the use of bio-based preservatives in the food, cosmetic and pharmaceuticals industries, regulatory and safety barriers need to be addressed. All this means that in order to navigate the complex regulatory landscape effective collaboration with regulatory agencies like FDA and EFSA is necessary. These companies are very important in approving new ingredients and that they are safe for human consumption. Early engagement with these bodies during the development process assists in safety risk clarification and the reaching of a streamlined approval pathway for bio based preservatives. To engender trust, as well as to ease the regulatory paths, the researchers suggest, transparency in communication and sharing of data on the efficacy and safety of the preservatives [23]. The overcoming of safety challenges is also contributed by the improved testing protocols. Testing methods for bio-based preservatives therefore need to be robust and exhaustive in nature, going beyond antimicrobial assay to saliently probe for possible toxicity, allergenicity, or delayed effects. Refining of these protocols provide more accurate, more reliable data to the regulatory agencies. Furthermore, internationally accepted standards in testing will facilitate global safety requirements for bio-based preservatives being developed, leading to wider global market implementation.

Compounds	Effective against	Application in food	Maximum tolerance
Acetic acid, acetates, diacetates (E260)	Yeasts, bacteria	Baked goods, condiments, confections, dairy products, fats/oils, meats, sauces	0.32%
Benzoic acid, benzoates (E210-E213)	Yeasts, molds	Beverages, fruit products, margarine, flavoured soft drinks (soft drinks or syrups),	0.1%
Dimethyl dicarbonate, Lactic acid, lactates (E270)	Yeasts, bacteria	fermented foods, beverages Meats	
Lactoferrin	Bacteria	Meats	
Lysozyme	Clostridium botulinum, other bacteria	Cheese, cooked meat, and poultry products	
Natamycin (E235)	Molds	Cheese	
Nisin (E234)	Clostridium botulinum, other bacteria	Cheese, cooked meat, and poultry products	1%
Nitrite, nitrate (E249- E252)	Clostridium botulinum	Cured meat	120 ppm
Parabens (alkyl esters (propyl, methyl, heptyl) of p-hydroxy benzoic acid	Yeasts, molds, bacteria (Gram-positive)	Beverages, baked goods, syrups, dry sausage	0.1%
Propionic acid, propionates (E280-E283)	Mold	Bakery products, dairy products	0.32%
Sorbic acid, sorbate (E200-E203)	Yeasts, molds, bacteria	Most foods, beverages, wines beverages (fruit juices, wine and cider), pastries and partially cooked bakery,	0.2%
Sulûte (E221-E226) Sulphur dioxide (E220)	Yeasts, molds	Fruits, fruit products, wines, dry fruits	200-300 ppm

NOTE: GRAS (Generally Recognized As Safe) per Section 201 (32) (s) of the U.S. Federal Food, Drug, and Cosmetic Act.

Figure 5 Some GRAS chemical food preservatives

A final, critical tool to overcome the barriers to the safety of bio based preservatives is also public education. However, because of incorrect or unknown information, there is often misuse and misinformation about natural preservatives'

potential risks and benefits. If industry stakeholders educate consumers about the safety, efficacy and sustainability benefits of these bio based preservatives, they will gain consumer confidence and support for these alternatives. Skepticism and skepticism can be managed by public awareness campaigns, scientific outreach, and transparency on testing, and regulatory approvals. In short, regulatory and safety barriers to bio based preservatives need to be tackled from multiple angles. Such strategies include collaborating with regulatory bureaus concerning bio based preservatives, improving testing protocols and educating the public about the safety as well as benefits of appropriate bio based preservatives in diverse industries.

4.3. Improving Cost-Effectiveness

In order to improve cost effectiveness of bio based preservatives, several strategies can be applied, including for instance optimization of production processes, use of sustainable raw materials and use of economies of scale. Reduction in the costs associated with the use of bio-based preservatives can be realized without any loss in effectiveness or environmental benefits by these approaches. Reducing costs is all about optimizing your production processes. For instance, fermentation development techniques can help increase the production efficiency of bio sources of preservatives, obtained from natural plant extracts. Manufacturers can still lower production costs and increase the availability of these preservatives for large-scale use by refining the fermentation process and increasing yield. Furthermore, bioreactors and process optimization technologies can facilitate the cycle of production to be faster and much more efficient, thereby decreasing costs and maintaining quality [24]. Another issue in making bio based preservatives an affordable alternative, is use of sustainable raw materials. Through sourcing locally from renewable raw materials, producers can reduce their dependence on costly, non-renewable resources, and save the transportation costs. For example, low cost alternatives to synthetic preservatives, such as essential oils containing antimicrobial properties are being increasingly explored from plant based compounds, some of which are discussed briefly here. In addition to lowering cost, these materials also help deliver sustainability by being biodegradable with a lower environmental footprint than petrochemical-derived preservatives [25]. Another opportunity that can be taken to reduce cost is Economies of scale. As demand for bio–based preservatives increases, larger production volumes will allow manufacturers to spread fixed costs and lower the cost per unit. It has been seen for example in bioplastics with companies that have scaled up production driving down the cost meaning that bio based products have become more competitive with conventional alternatives.

Bio based active food packaging materials is a case study demonstrating cost saving approaches. This is a sustainable substitute to conventional, petrochemical based packaging, made from renewable materials. The cost of bio-based packaging has declined as production volumes increased and technology is improved, to demonstrate how the laws of economies of scale and innovation can lower costs in the bio-based preservation industry [25]. We conclude that achieving cost effectiveness of bio-based preservatives will require a combination of production process optimization, exploitation of sustainably derived raw materials, and economies of scale. This makes bio based preservatives more available and adapted to these large industries such as food preservations, which helps to lower the costs in the long run.

5. Analysis and Discussion

5.1. Synthesis of Key Challenges and Solutions

Despite being promising from a sustainability and safety point of view, bio based preservatives are not readily adopted due to several hurdles. Such challenges cut across regulatory barriers, cost effectiveness and scalability and limited efficacy in some applications. However, there have been numerous proposed solutions to fix these problems and what the future of bio based preservatives will be in several industries will be decided by how effective these solutions are. The one of the key challenge is regulatory approval. However, bio based food preservatives must also be made safe by agencies such as the FDA and EFSA. Bio based preservatives are very often subjected to strict testing protocols, which in turn can result to long approval timelines thereby shrinking their market entry. But these barriers can be overcome by collaboration with regulatory agencies, expansion of safety testing protocols and educating the public. But by collaborating on an early basis with regulators and sharing safety data, manufacturers can speed the approval process. In addition, public and stakeholder education on the safety of bio-based preservatives can help develop of trust and improve the chances of their adoption [26].

Yet both are significant challenges in the cost and scale at which bio based preservatives can be deployed. The price of raw materials and their processing are the main reasons that the production costs of bio based preservatives are now more expensive than synthetic ones. In this regard, production processes can be optimized, sustainable raw materials should be utilized, or the economies of scales should be made use of. Then, the cost of bio-based preservatives can be

reduced through improving production techniques and raising output volumes and, hence, making them economically feasible on a large scale for use in food, cosmetics and pharmaceuticals [26]. Efficacy is also a concern. However, while some bio based preservatives have been effective, their shelf life and stability in particular applications can be limited due to their limited volatility and inconsistent properties. Nanotechnology, blending natural compounds, fermentation technologies – these innovations can make bio based preservatives more stable and more effective. In many instances, these innovations can enhance the performance of these compounds to the point where they compete with synthetic preservatives. But more work needs to be done on these technologies, to fine tune them and get them to industry standard. Overall, regulatory hurdles and cost, along with scalability and efficacy are major hurdles to commercializing bio-based preservatives. But regulatory collaboration, optimized production processes, and technological innovations represent a solution to these problems. As such, bio-based preservatives are beginning to emerge as a potential and sustainable alternative solution to synthetic chemicals in food and other industries. Continued development of effective, cost efficient, and safe bio-based preservation technologies will be necessary for the success of these efforts.

5.2. Comparison with Synthetic Preservatives

Each have their various pros and cons so it depends on the application, i.e., safety, cost and effectiveness for bio-based preservatives or synthetic alternatives. Their natural origin makes them a major asset among the bio-based preservatives that act in tune with the growing demand of consumers for clean label and environment friendly products. They are included from plant, microbial or animal sources and have possible health positive benefits from antioxidants and antimicrobial property. For these reasons, bio based preservatives are thought to be safer than synthetic additives, which tend to lead to allergic reactions or other bad effects on health. Moreover, bio-based preservatives are biodegradable and environmentally friendly, which has less environmental footprint than the synthetic chemicals that lead to pollution and are difficult to degrade [27].

On the flipside, however, bio based preservatives aren't without their limitations, either. One big issue with anticorrosion chemical coatings is cost. The high cost of raw material and production processes makes producing bio based preservatives costlier compared to synthetic preservatives. Therefore, these preservatives are not cost effective on large industrial scale, especially in the low margin industries such as food packaging and cosmetics. In addition to this, some applications such as enhancing shelf life or avoiding microbial growth in a range of conditions may be less effective with bio based preservatives than synthetic alternatives [27]. However, in comparison to the synthetic preservatives, which are well proven in cost, effectiveness and scalability, are they. Because they are cheap to produce, highly stable, and provide long lasting preservation they are widely used. However, there does exist a synthetic variety that can be concerning for your health, as some have been linked to allergies, hormonal disruptions, and long term toxicity. In addition, widespread use of them has been accompanied with growing concerns regarding emerging microbial resistance. In general, bio-based preservatives present a more ecological and industrially easily accessible alternative; however, they present at a higher cost and variable effectiveness. While cheaper and more effective in some cases, synthetic preservatives are health and environment risky. Indeed, the solution may be in the mid ground, where we balance different types of preservatives to meet different needs, led by ongoing innovation to make bio based options increasingly efficacious and affordable.

5.3. Future Trends and Opportunities

Technological advancements, new research directions and market opportunities are promising for the future of bio based preservatives aligned with green chemistry and renewable sources. In the face of increasing consumer demand for more naturally and sustainably packaged products, bio-based preservatives may emerge as a primary alternative to synthetic chemicals in food, cosmetics and pharmaceuticals. An area of promise for advancement is to develop advanced packaging materials with capability of incorporating antimicrobial properties. Bio-based preservatives are already instrumental in adding value to antimicrobial packaging innovations in the market, which enable enhancement of food shelf life without using synthetic additives. Among these are the natural polymers and coatings, e.g., chitosan and essential oils, which preserve food and at the same time lead to lesser waste and make the whole process more sustainable. The demand of such packaging solutions is growing as consumer awareness towards environment issues is increasing [28].

Additionally, great potential for bio based preservatives exists in bioengineering and nanotechnology technological progress. For instance, nanoparticles can serve as agents to improve the stability and loading of natural preservatives, thereby realizing efficient preservation with lower concentration of the preservatives. Given, this could tackle one of the largest short comings of bio-based preservatives; their potency in a range of circumstances and product types [28]. And on the broader research agenda, new sources of antimicrobial compounds are being found, both in plants and in microorganisms, which promise to be even stronger, more versatile, and more economical than the existing alternatives. In addition, the growth of the global bio based preservatives market is intertwined with the trend towards sustainability

globally. Since industries increasingly attempt to reduce their environmental impact, bio-based solutions are a much better choice and better environmentally friendly than synthetic preservatives that often generate pollutants. Especially in the food packaging and personal care, consumers are rapidly aligning themselves towards health conscious, ecofriendly products. Finally, although the future of these bio based preservatives appears bright, industry adoption is increasingly driven as a result of emerging innovations in packaging, nanotechnology and bioengineering. With further research, such preservatives will probably be essential in sustainable product development providing functional as well as environmental benefits.

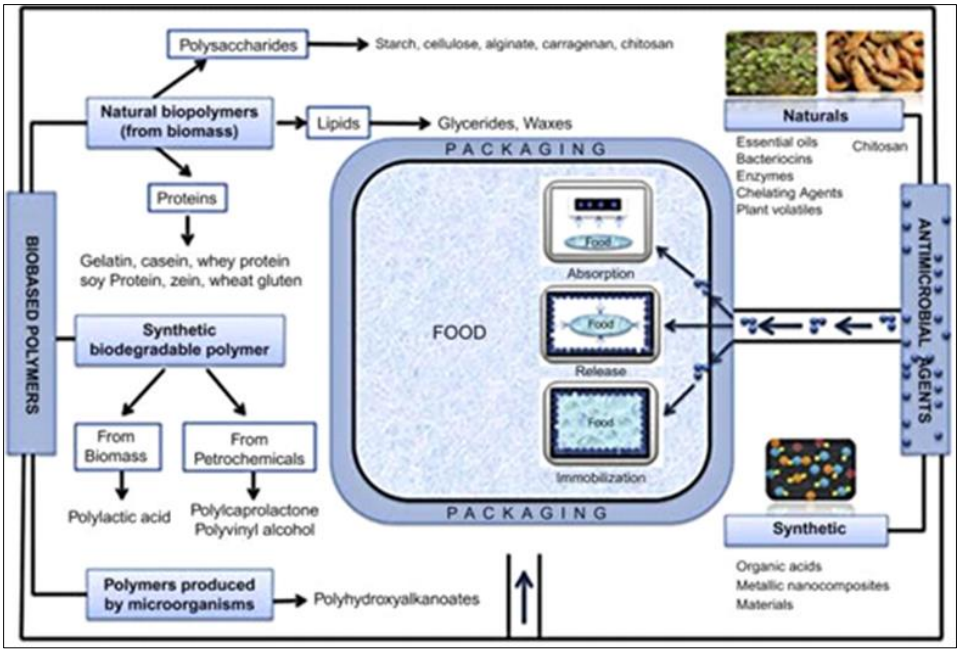

Figure 6 Innovations in food packaging

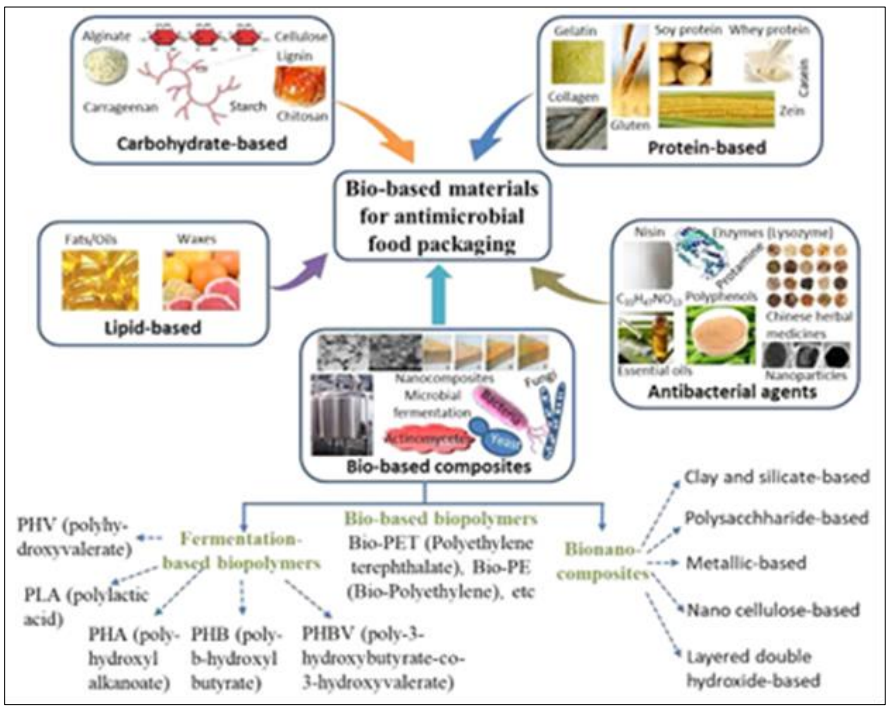

Figure 7 Novel bio-based materials in antimicrobial food packaging

6. Conclusion

6.1. Summary of Key Findings

In addition, this study emphasizes the increasing possibility of bio based preservatives as a substitute to synthetic additives. Key findings show several benefits, as well as problems, of bio based preservatives as it relates to use in industries such as food, cosmetics and pharmaceuticals. These preservatives, which are derived from natural sources like plants, essential oils, and microorganisms, offer a range of benefits:

- Health Benefits: Generally bio-based preservatives have been considered to be safer alternatives, less likely to trigger allergies, toxicity or other health adverse effects, compared with synthetic preservatives. This is in tune with the growing preference among consumer for natural and organic products.
- Efficacy: Natural preservatives possess high antimicrobial and antioxidative properties, which allow increasing shelf life of nutritive food products, maintaining their nutritional quality.
- Environmental Impact: Preservatives that are bio based help reach a sustainable solution by decreasing our dependence on petrochemical based products. On the other hand, these preservatives are from renewable sources and therefore contribute to practices that are environmentally friendly manufacturing.

Nevertheless, there still remain several obstinate such as cost and scalability. Widespread use of bio-based preservatives is hampered by high production costs as well as limited availability of raw materials. Moreover, their approval and use in the market are marred by regulatory hurdles and the requirement for sturdy safety testing. This study is significant because bio-based preservatives may well be a game changer in food safety and sustainability. Despite a host of benefits, the production and regulatory roadblocks must be faced to realize broader use.

Bio based preservatives offer food manufacturers an opportunity to respond to the increasing consumer demand for natural and eco-friendly food products. These findings can be capitalized on by manufacturers who collaborate with research institutions to investigate cost effective production methods and bio based preservative formulations. Safe and efficient regulation is critical to the take-up of bio based preservatives as regulators need to update standards and simplify approval processes. Given clear regulatory guidelines for bio based preservatives they would be a much safer way to preserve foods and would help speed up their entry into the market. Switching to bio based preservatives, however, holds the promise of safer, healthier and more sustainable food and cosmetic products for consumers. Education through public awareness campaigns and consumer education would promote the image of a bio based preservative as a boon to consumer confidentiality and facilitate wider acceptability.

6.2. Recommendations and Future Research Directions

Future research leading to the enhanced adoption of bio-based preservatives should include the research into ways to optimize production methods in order to decrease costs. This could include developing novel raw materials based around sustainability, or tapping into the world of biotechnology to perform things like fermentation and enzymatic processes. New nanotechnology will improve the stability and delivery efficiency of bio based preservatives which will overall increase its effectiveness in food and other related product preservation. However, research in blending natural compounds could form the basis for creating synergistic effects and actually enhancing the antimicrobial and antioxidant properties. Work is needed with researchers, food manufacturers, and regulatory bodies to overcome regulatory challenges. Having clear bio based preservatives safety testing protocols and guidelines will aid in faster approval of bio based preservatives. Finally, there should be efforts to promote consumer education to greater awareness of the benefits associated to the use of bio-based preservatives. Demand in this market will likely be driven by informing consumers about their safety, health and environmental advantages. With innovation around these challenges and by embracing technological advances, bio based preservatives will have significant place in food preservation of the future, enabling health conscious, sustainable alternatives to synthetic additives.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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