

Silicon Dioxide in Active Food Packaging: A Review on Mesoporous Carriers for Encapsulated Antioxidants and Antimicrobials

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Abstract

The increasing demand for packaging technologies that actively maintain food quality and safety has highlighted the potential of silicon dioxide (SiO₂) as a multifunctional material. This review discusses the physicochemical properties, mechanisms of action, application formats, functional performance, and regulatory aspects of SiO₂ in active food packaging. Amorphous and mesoporous forms of SiO₂ exhibit high surface area, strong adsorption capacity, and thermal stability, enabling their use as moisture and oxygen absorbers as well as carriers for antimicrobial and antioxidant compounds. Reported applications include silica gel sachets for moisture control, coatings and films reinforced with nanosilica, and mesoporous silica nanoparticles (MSNs) for controlled release of bioactive agents. Experimental evidence demonstrates that these systems can effectively reduce microbial growth, delay fruit ripening, and slow lipid oxidation, thereby extending shelf life while maintaining sensory quality. At the same time, nanosilica raises safety concerns due to potential migration and bioaccumulation, prompting stricter toxicological testing and regulatory oversight by bodies such as FDA, EFSA, and BPOM. The main finding of this review is that amorphous and mesoporous SiO₂ consistently provide superior functionality compared to crystalline forms, while regulatory compliance and consumer acceptance remain key challenges. Overall, SiO₂ shows strong promise as a safe and effective active packaging component, with future opportunities in smart and biodegradable packaging innovations.

Keywords: Silicon Dioxide; Mesoporous Silica Nanoparticles; Active Food Packaging; Encapsulation; Food Security

Introduction

Ensuring food quality and safety is a major global challenge in the modern food supply chain [1]. Rapid urbanization, population growth, and evolving dietary preferences have increased demand for convenient, ready-to-eat products with extended shelf life [2]. However, prolonged distribution and improper storage often accelerate deterioration, leading to microbial spoilage, chemical degradation, and physical damage. Postharvest losses of fresh produce alone are estimated at 25% - 30% worldwide, largely due to microbial contamination and inadequate packaging [3,4]. This underscores the need for packaging systems that go beyond passive protection and actively preserve product quality and safety.

Active packaging has emerged as an innovative solution by releasing or absorbing targeted substances such as moisture, oxygen, ethylene, or antimicrobial agents [5]. For instance, oxygen scavengers can reduce residual O₂ in headspace from ~21% to < 1% within 48 h, while moisture absorbers maintain relative humidity below 30%, effectively preventing mold growth in bakery products [6,7]. Such functionality is achieved through active agents including inhibitors, scavengers, and carriers of bioactive compounds. Among these, silicon dioxide (SiO₂) has received growing attention due to its multifunctionality and compatibility with food systems [8].

SiO₂ naturally exists in crystalline (e.g., quartz) and amorphous (e.g., silica gel) forms [9]. It has long been used in the food industry as an anti-caking agent (E551) and is classified as Generally Recognized as Safe (GRAS) by both the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA) [10,11]. Its physicochemical properties - including high adsorption capacity (up to 40% of its weight in water), oxygen absorption, large surface area (> 200 m²/g for fumed silica and > 1,000 m²/g for mesoporous silica), and chemical/thermal stability - make it particularly suitable for active packaging [12]. Depending on its form, SiO₂ can function as an oxygen and moisture scavenger or as a carrier matrix for antioxidants, antimicrobials, and ethylene inhibitors [13].

Recent advances in nanotechnology have expanded SiO₂'s potential through mesoporous silica nanoparticles (MSNs) with pore sizes of 2 - 50 nm.

These allow controlled release of bioactive compounds and improved functional stability [14]. Experimental evidence shows that MSNs loaded with essential oils inhibited *Escherichia coli* by more than 3 log CFU/g and extended chicken shelf life by up to 7 days under refrigeration, while silica sachets containing potassium permanganate delayed tomato ripening by 5 - 7 days at room temperature [15,16]. Such findings demonstrate the quantitative effectiveness of SiO₂-based active packaging in real food systems.

Despite these advantages, challenges remain for industrial application. Toxicological concerns regarding nanosilica (< 100 nm), variability of performance under real storage conditions, and limited consumer acceptance are key barriers. Studies indicate that nanosilica at high concentrations may cause oxidative stress or inflammation, though amorphous forms are largely inert at lower exposure levels [17]. Regulatory authorities therefore impose strict migration limits, requiring compliance with maximum thresholds to ensure consumer safety [18].

However, comprehensive reviews that integrate both qualitative insights and quantitative evidence on SiO₂'s functional mechanisms, safety considerations, and practical applications in active packaging remain limited. Addressing this gap is crucial to provide a stronger scientific basis for its safe and effective industrial adoption.

This review therefore critically examines the role of SiO₂ in active packaging, focusing on its physicochemical properties, mechanisms of action, applications, effectiveness in microbial control and shelf-life extension, and regulatory aspects. By highlighting both opportunities and limitations, it aims to guide future development of SiO₂-based active food packaging technologies.

Data collection method

This literature review was conducted through a comprehensive search of relevant scientific publications from internationally recognized databases, including Scopus, Web of Science, ScienceDirect, and PubMed. The search covered articles published between 2000 and 2025 using keywords such as "silicon dioxide," "SiO₂," "active packaging," "food packaging technology," "nanosilica," and

“*mesoporous silica*.” A total of 312 records were initially identified, of which 184 were excluded after screening for duplication, non-English language, or lack of relevance. The remaining 128 articles were assessed in full text, and 112 articles were finally included in this review.

Inclusion criteria were: (i) studies addressing SiO₂ in food packaging applications, (ii) discussion of physicochemical properties, mechanisms, applications, safety, or regulatory aspects, and (iii) original research articles or review papers published in peer-reviewed journals. Exclusion criteria were: (i) studies unrelated to food packaging, (ii) papers lacking experimental or scientific validation, (iii) abstracts, conference proceedings without full papers, and non-peer-reviewed sources.

To ensure reliability, references were cross-checked, and priority was given to high-quality sources such as peer-reviewed journals, recent publications (particularly within the last 10 years), and reports from recognized regulatory authorities (e.g., FDA, EFSA, OECD).

Properties and characteristics of SiO₂

SiO₂ is an inorganic compound with a very distinctive structure and properties, including variations in crystalline and amorphous forms, diverse production methods, high thermal stability and chemical resistance, and safety aspects that need to be considered.

Chemical structure and physical form

Silicon dioxide (SiO₂) is composed of 1 silicon atom tetrahedrally bonded to 2 oxygen atoms [14]. Structurally, it exists in 2 principal forms, crystalline and amorphous [6,15]. Crystalline SiO₂, such as quartz, tridymite, and cristobalite, generally exhibits crystallinity levels above 90% with surface areas of only 1 to 10 m²/g, resulting in limited adsorption

capacity of less than 2% water uptake at 60% relative humidity. In contrast, amorphous SiO₂, including silica gel and fumed silica, shows crystallinity levels below 10% and provides a markedly higher surface area, ranging from 200 to 500 m²/g, while mesoporous silica can exceed 1000 m²/g. This configuration enables water adsorption of up to 40% of its own weight and allows SiO₂ to function effectively as both an oxygen scavenger and a carrier matrix for bioactive compounds [16].

These quantitative distinctions indicate that amorphous and mesoporous SiO₂ forms are indispensable for active packaging applications, since crystalline structures lack sufficient adsorption and release capacity. For instance, mesoporous silica nanoparticles (MSNs) commonly achieve encapsulation efficiencies above 70% and can extend the release of antioxidants or antimicrobials for more than 7 days under refrigerated conditions [16]. Studies also report microbial reduction exceeding 3 log CFU/g in foods treated with MSN-based active films, compared with less than 1 log CFU/g in controls [16]. A minimum proportion of amorphousness is therefore required, and higher amorphous content is directly correlated with improved adsorption and controlled release performance. Similar patterns have been highlighted in research on other bioactive systems, where functional outcomes such as antioxidant inhibition (IC₅₀ values ranging from 0.4 to 2.6 µg/mL) and bioactive compound retention were strongly influenced by structural accessibility and concentration of active constituents [17,18]. These parallels reinforce that, within the framework of food packaging, SiO₂ with predominantly amorphous or mesoporous structures demonstrates the highest potential as a carrier for encapsulated antioxidants and antimicrobials. An illustration of the tetrahedral structure and the distinction between crystalline and amorphous SiO₂ can be seen in **Figure 1**.

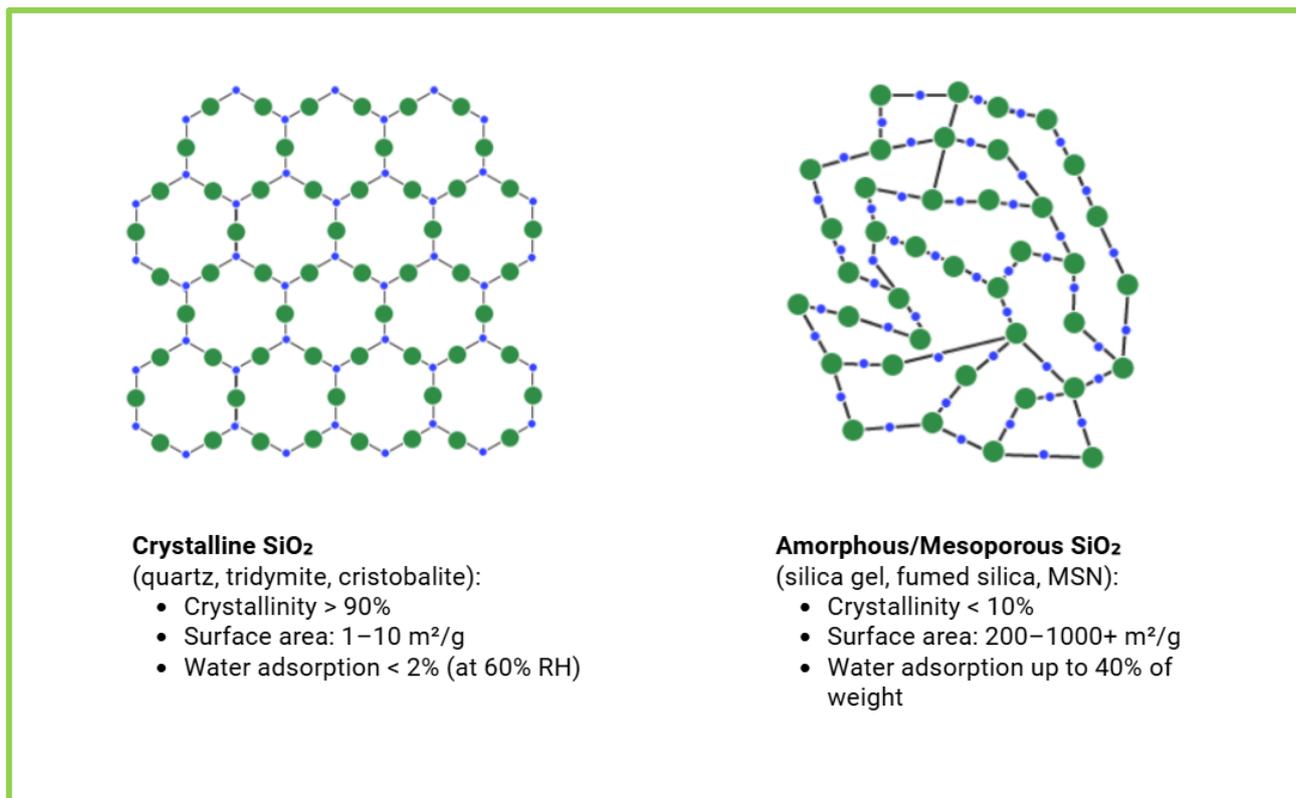


Figure 1 Tetrahedral structure of SiO₂ and the distinction between crystalline and amorphous forms.

Production method

Various forms of SiO₂ can be obtained through synthetic processes that produce different physical and chemical characteristics, including: Precipitated silica: Strong acid and sodium silicate react to form precipitated silica, which is made up of amorphous silica particles that range in size from microns to nanometers [19]. Usually utilized in packaging films as a filler or absorbent substance [20].

Fumed silica (pyrogenic silica): In order to create fume silica, also known as pyrogenic silica, volatile silicon compounds like silicon tetrachloride (SiCl₄) must be burned in an oxygen and hydrogen atmosphere [21]. This product comes in the form of an ultra-fine amorphous powder with a high specific surface area (> 200 m²/g), making it appropriate for use as a carrier

agent for active ingredients or as a mechanical reinforcement in film packaging [22].

Mesoporous silica: These mesoporous silicas, such as MCM-41 and SBA-15, contain pores that range in size from 2 to 50 nm with an extremely high surface area (> 1,000 m²/g) [23]. This structure is better to other antibacterial and antioxidant release systems in active packaging because it permits the regulated release of active ingredients [24]. An overview of these production methods and the resulting forms of SiO₂ can be seen in **Figure 2**.

The kind and form of SiO₂ used has a significant impact on the packaging system's functional performance in terms of chemical stability, adsorption, and diffusion.

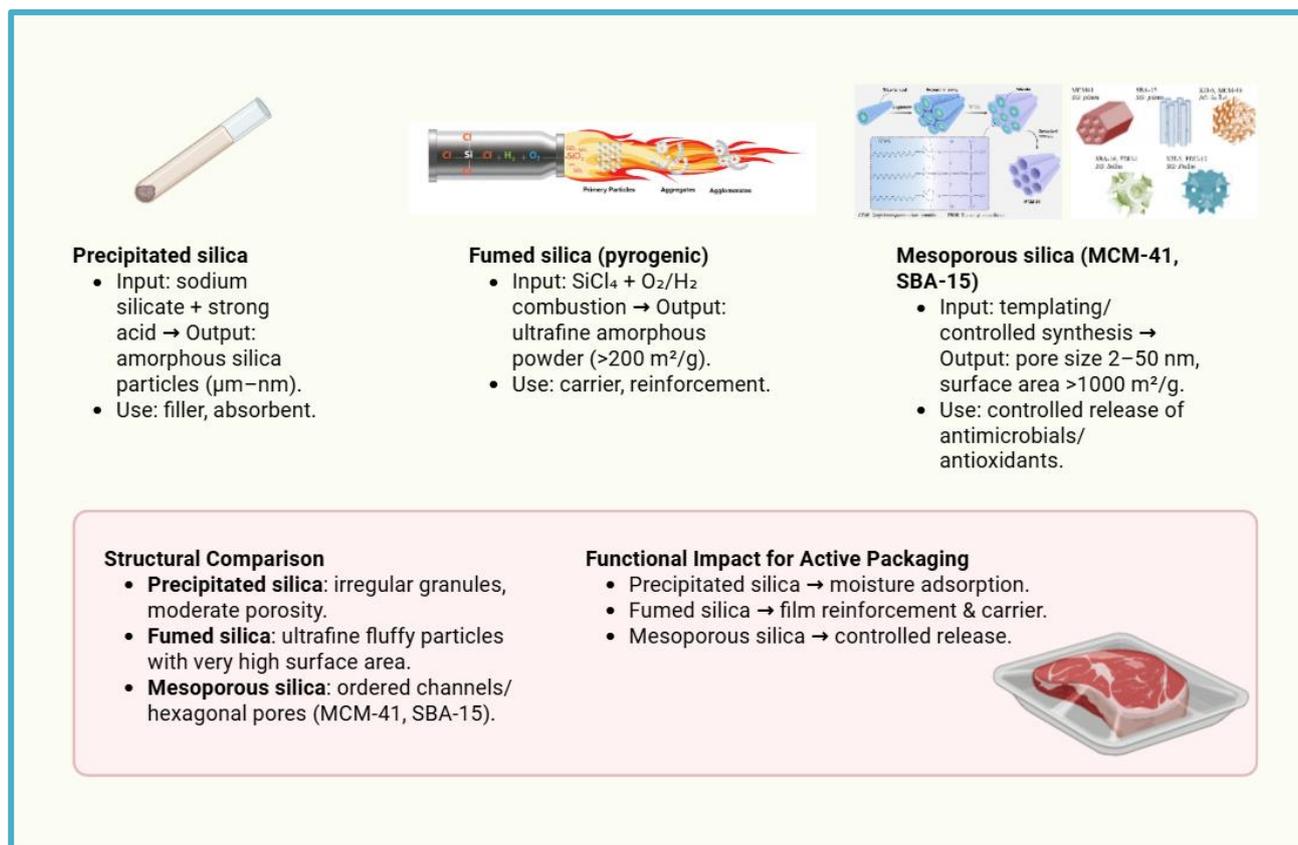


Figure 2 Production methods of SiO_2 : Precipitated, fumed, and mesoporous forms with their functional characteristics.

Thermal and chemical stability

The resilience of SiO_2 against high temperatures and harsh environmental conditions is one of its key benefits. Silica is chemically inert in the pH range of 3 to 9 and does not readily decompose at temperatures higher than $1,000 \text{ }^\circ\text{C}$ [25]. Because of this characteristic, SiO_2 can be utilized in a broad range of food products, including thermally sterilized ones. Furthermore, the silica surface can be chemically altered (surface functionalization) to improve its affinity for specific active substances like phenolics, ethylene inhibitors, or essential oils [26].

Safety and toxicology aspects

SiO_2 has long been utilized in the food industry as both a packaging component and an additive (E551), and is generally considered safe by major regulatory bodies [27]. The European Food Safety Authority (EFSA) permits its use in food-contact materials with a specific migration limit (SML) of up to 10 mg/kg food for amorphous forms, whereas the U.S. Food and Drug Administration (FDA) classifies SiO_2 as Generally Recognized as Safe (GRAS) under 21 CFR §182.90

[28,29]. However, special attention is required when using nanoscale SiO_2 (particle size $< 100 \text{ nm}$), due to its higher surface reactivity and potential to cross biological barriers.

Toxicological studies have shown that nanosilica particles below 50 nm in diameter and at concentrations exceeding $100 \text{ }\mu\text{g/mL}$ can induce oxidative stress, inflammatory responses, or cytotoxic effects in various cell lines [30]. *In vivo* studies also report tissue accumulation in the liver, spleen, and gastrointestinal tract when exposure levels exceed 50 mg/kg body weight [31]. The degree of toxicity is strongly influenced by particle size, surface charge, aggregation state, and exposure route.

Therefore, the development of nanosilica-based packaging must adopt a precautionary approach, which includes quantitative migration testing using food simulants (e.g., 3% acetic acid or 10% ethanol), assessment of specific and total migration levels, and comprehensive *in vitro* and *in vivo* toxicological evaluations. These measures should comply with the latest guidelines established by EFSA and the Organisation for Economic Co-operation and

Development (OECD), which recommend that nanosilica migration remain below the threshold of 10 mg/kg food and that particle sizes be clearly characterized during risk assessment [32,33].

The working mechanism of SiO₂ in active packaging

The special physicochemical characteristics of SiO₂, including its large specific surface area, robust adsorption capacity, and excellent thermal and chemical durability, allow it to serve a number of purposes in active packaging processes [10]. SiO₂ has several uses in food packaging technology, such as an

encapsulation method for bioactive substances, an agent that absorbs moisture and gases, and an active ingredient in films or sachets that interact either directly or indirectly with the microenvironment within the packaging [11]. This mechanism plays a major role in controlling the sensory quality, extending the shelf life, and lowering the danger of microbial contamination in packaged food products. **Table 1** explains the various working mechanisms of SiO₂ in active food packaging systems, based on their application form, main function, and examples of their use in various types of food products.

Table 1 Working mechanism and application of silicon dioxide in active food packaging.

Working mechanism	The form of SiO ₂ used	Main function	Examples of food applications
Adsorption of moisture and gas	Silica gel and fumed silica	Reduces relative humidity and O ₂ levels in the packaging	Instant coffee, biscuits, and dry food
Encapsulation of antimicrobial/antioxidant compounds	Mesoporous silica nanoparticles (MSNs) and modified silica	Protection of active compounds and controlled release	Meat, dairy, fish, and bread products
Modification of the barrier properties of packaging films	Nanosilica in biopolymer films (e.g. chitosan, PVA)	Improve mechanical properties and barrier against water/gas	Fresh vegetables, cheese, and bread
Micro-environmental interactions of packaging	Silica sachet + active compound (e.g. KMnO ₄)	Regulates the internal atmosphere and slows down ripening or spoilage	Fresh fruit (tomatoes, bananas), vegetables
Indirect antimicrobial activity	SiO ₂ + metal ion (Ag ⁺ , Zn ²⁺)	Suppresses the growth of pathogenic bacteria through the release of toxic ions	Processed meat products and ready-to-eat foods

As a moisture and oxygen absorbing agent

SiO₂ functions primarily through the physical adsorption of gas and water molecules [34]. Through hydrogen interactions between water molecules and silanol groups (–Si–OH) on the particle surface, the amorphous pore structure of SiO₂, particularly in the form of silica gel and fumed silica, permits contact with water vapor in the air [35]. Amorphous SiO₂ such as silica gel is capable of adsorbing up to 40% of its own weight in water at moderate relative humidity, while crystalline SiO₂ adsorbs less than 2%,

highlighting the superior adsorption capacity of the amorphous form. Even at low relative humidity levels (less than 30% RH), SiO₂ has a very high capacity for adsorbing moisture, which makes it a useful desiccant material for packing dry foods, biscuits, instant coffee, and processed goods that are sensitive to moisture [36].

SiO₂ exhibits the ability to absorb oxygen in addition to water when functionally altered or mixed with other substances like sodium dithionite or iron oxide [27]. Studies also report that oxygen scavenging with modified SiO₂ can reduce residual oxygen in the

packaging headspace to below 1% within 48 hours, thereby slowing oxidation and microbial growth. This oxygen absorption is important in preventing fat oxidation, degradation of natural pigments (such as carotenoids and anthocyanins), and the growth of aerobic microorganisms [37].

As a carrier for antimicrobial and antioxidant compounds (encapsulation)

SiO₂ has the capacity to function as a carrier matrix for active substances that operate on the basis of

encapsulation, particularly when it takes the form of modified silica gel or mesoporous silica nanoparticles (MSNs) [38]. Bioactive substances such as phenolic acids, metal ions (Zn²⁺, Ag⁺), synthetic antioxidants (BHT, BHA), and essential oils (e.g., eugenol, thymol) can be trapped by the pore surfaces and walls of the mesoporous channels [39]. An overview of SiO₂-based encapsulation and its role in extending food shelf life is presented in **Figure 3**.

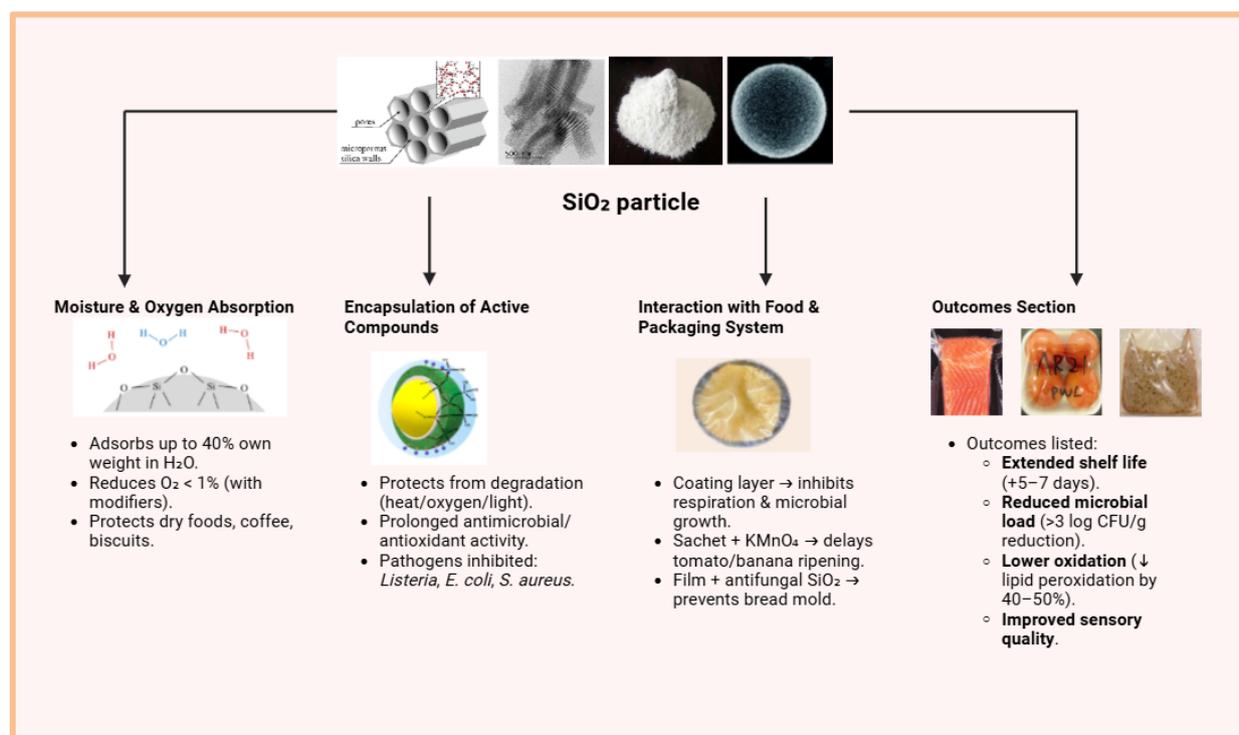


Figure 3 Illustration of SiO₂-based encapsulation of active compounds and their applications in food packaging.

The 2 primary benefits of this encapsulation are preventing the active ingredient from being prematurely degraded by heat, oxygen, or light; and allowing for controlled release into the package's headspace or straight onto the food's surface within a predetermined window of time [40].

According to a number of studies, biopolymer-based film packaging, including chitosan or PVA modified with SiO₂ and containing essential oils, has potent antibacterial properties against food pathogens like *Listeria monocytogenes*, *Staphylococcus aureus*, and *Escherichia coli* [41-43]. Furthermore, it has been demonstrated that the antioxidants released by MSNs

slow down the pace of lipid peroxidation and preserve the sensory appeal of fat-based items [44].

Interaction with food products and storage environment

The way SiO₂ interacts with food products in practical applications is largely determined by the packaging system's design, including whether the SiO₂ is incorporated into the packaging film itself, as a coating layer, or as a separate sachet. SiO₂ enhances the mechanical and barrier qualities of the polymer film (i.e., the ability to withstand gas and water) in addition to acting as an active agent in nanocomposite films [45]. Furthermore, SiO₂ can alter the packaging's

inner surface to provide a microenvironment that is more thermodynamically stable [38].

For instance, using silica sachets containing antiethylene compounds (such KMnO_4) absorbed in the silica's porous structure might prolong shelf life and prevent ripening in fresh products like fruit and vegetables [46]. Experimental evidence shows that such sachets can extend the ripening time of bananas and tomatoes by 5 - 7 days under ambient conditions compared to controls. On the other hand, the use of active films containing encapsulated antifungal SiO_2 can inhibit the growth of mold that damages bread products [47]. Studies report that bread packaged with antifungal SiO_2 films remains mold-free for up to 10 days, whereas untreated bread shows visible spoilage within 3 - 4 days.

Experimental evidence support

The efficiency of SiO_2 's operating mechanism in active packaging systems has been validated by a number of experimental investigations. Ma *et al.* [46] shown that gelatin film containing nanosilica modified with oregano oil might inhibit microbial development

and reduce lipid oxidation in fish that was packaged. According to Hadidi *et al.* [47], MSNs containing gallic acid that were used in milk packaging improved the stability of bioactive substances and inhibited the growth of microorganisms. Warsiki [48] extended the shelf life of tomatoes by up to 7 days at room temperature by using sachets made of silica gel and an ethylene binder.

Application of SiO_2 in active packaging

In recent decades, SiO_2 has seen tremendous advancement in active packaging technology, in tandem with the food industry's growing demand for packaging systems that can actively prolong shelf life, preserve quality, and enhance food safety in addition to being passively protective [51]. SiO_2 is used in a variety of formulations and packaging technologies that are tailored to the functionalities and properties of food products [52]. **Table 2** presents a systematic classification of the various forms of SiO_2 applications in active food packaging, based on product category, application format, main function, and additional innovations that support the efficacy of the technology.

Table 2 Applications and technology of SiO_2 in active food packaging.

Application categories	SiO_2 format	Main function	Examples of food products	Additional components
Dry food	Powder / granules in sachets	Moisture absorbent and anti-caking	Biscuits, cereals, and spices	SiO_2 sachet + essential oil / metal ion
Fresh food	SiO_2 based coating layer	Inhibits respiration, maintains moisture, and suppresses microbes	Fresh fruits and vegetables	Coating SiO_2 + enzymes or organic acids
Processed/served food	Polymer nanocomposite film with SiO_2	Active antimicrobial, water vapor/gas barrier, and control of active substance release	Processed meat, milk, and frozen foods	Biopolymer + nanosilica / MSNs
Sealed packaging	Active sachet (SiO_2 + bioactive compounds)	Moisture absorber + simultaneous antimicrobial release	Cheese, snacks, and meat products	SiO_2 + eugenol, thymol, AgNP
Smart and active packaging	Mesoporous silica nanoparticles (MSNs)	Active substance delivery system that is responsive to the environment	Seafood	MSNs + cinnamaldehyde, ferulic acid, essential oils
Advanced antimicrobial combinations	Active carrier (modified SiO_2)	$\text{Zn}^{2+}/\text{Ag}^+$ ion release regulator, increasing the stability of bioactive compounds	Microbial sensitive processed products	SiO_2 + ZnO , AgNP, proteolytic enzymes

Application to various food products

SiO₂ has been used extensively in active packaging for dry food items such as cereals, biscuits, and spices, where its water adsorption capacity can reach up to 40% of its own weight, effectively preventing caking and maintaining product flowability [53]. In fresh food products such as fruits and vegetables, sachets containing SiO₂ combined with ethylene scavengers have been reported to delay ripening by 5 - 7 days and reduce microbial load by more than 2 log CFU compared to untreated controls [54]. In processed and ready-to-eat foods, such as dairy and meat products, antimicrobial SiO₂ systems have demonstrated inhibition of *Listeria monocytogenes* and *Escherichia coli* by more than 90%, thus contributing significantly to food safety [55].

SiO₂-based packaging format

Polymer films and nanocomposites containing SiO₂ have shown improvements in tensile strength by 15% - 25% and reductions in oxygen permeability of up to 30% when compared with neat biopolymer films [45]. Uniform dispersion of SiO₂ within the matrix is critical to achieving these effects [56]. As a surface coating, SiO₂ has been demonstrated to reduce microbial contamination on fresh produce surfaces by up to 2 log cycles, while also controlling the release of active compounds [57,58]. Sachets and pads with granular or powdered SiO₂ can maintain relative humidity below 30% inside packages, thereby preventing mold growth, while the latest formulations enriched with essential oils or metal ions further extend shelf life by 3 - 5 days compared to conventional sachets [59,60].

Combination with other active ingredients

When combined with zinc oxide (ZnO) or silver nanoparticles (AgNPs), SiO₂ matrices have achieved complete inhibition (> 99%) of Gram-positive bacteria such as *Staphylococcus aureus* and Gram-negative bacteria such as *E. coli* within 24 - 48 h [62,63]. Encapsulation of essential oils such as eugenol or thymol within a SiO₂ matrix not only improves stability during storage but also enables controlled release for up to 10 days, significantly prolonging the antimicrobial activity [60,61]. Similarly, formulations

with organic acids and enzymes incorporated into SiO₂-based systems have been shown to suppress fungal growth on bread and cheese by more than 80% [64].

Latest innovations: Nanosilica and mesoporous silica nanocarriers

Nanosilica with particle sizes below 100 nm exhibits water adsorption up to 1.5 times higher than micron-sized silica, while also enhancing polymer film barrier properties by reducing water vapor transmission rates by 20% - 35% [65,66]. Mesoporous silica nanoparticles (MSNs), with pore sizes of 2 - 50 nm and surface areas exceeding 1,000 m²/g, can achieve encapsulation efficiencies greater than 70% for active molecules [67]. Controlled release studies show that MSNs can deliver antioxidants such as ferulic acid or cinnamaldehyde steadily over a period of 5 - 10 days, depending on humidity and temperature [68]. Applications in chilled meat and seafood packaging have demonstrated reductions in lipid oxidation by up to 40% and microbial growth suppression by 2 - 3 log CFU, without negatively affecting sensory quality [69]. Recent innovations using MSN-modified films have further extended the shelf life of fish and poultry by 5 - 7 days under refrigeration [70-72].

Effectiveness and performance of silicon dioxide in active packaging

Numerous experimental techniques have been used to thoroughly examine the efficacy of SiO₂ as an active ingredient in food packaging systems, both in lab settings and in large-scale storage simulations. This assessment covers SiO₂'s capacity to lower oxygen and humidity levels in the packing headspace, its indirect antimicrobial activity via active component encapsulation, its impact on food's organoleptic quality, and its relative effectiveness in comparison to other active ingredients [70]. Overall, research indicates that SiO₂ significantly prolongs food goods' shelf lives while preserving their chemical, physical, and microbiological qualities [74].

Laboratory test results: Microbial depletion, oxygen and water content, and sensory tests

In lab experiments, it was demonstrated that SiO₂, a moisture-absorbing substance (desiccant), decreased the packaging's relative water content, resulting in less conducive conditions for the growth of microbes [72]. For instance, it has been demonstrated that using silica gel in sachets in biscuit and chip packing can lower relative humidity from over 60% to less than 30% in a day, greatly preventing the growth of Gram-negative bacteria and mold (*Aspergillus niger*) [76,77].

Utilizing SiO₂ as an encapsulating matrix for active chemicals greatly boosts its efficacy in antibacterial applications [78]. According to a study by Lu *et al.* [79], processed chicken held for 7 days at 4 °C exhibited a 3 log CFU/g decrease in *E. coli* counts when gelatin films with thyme oil-loaded mesoporous silica nanoparticles (MSNs) were used, as opposed to a 1 log CFU/g decrease in the control. Packaging using SiO₂-based active film did not significantly alter the product's flavor, texture, or odor in sensory testing, suggesting good sensory compatibility [80].

Comparison with other active ingredients

SiO₂ has a number of performance advantages over other active materials as zeolite, activated carbon, or clay minerals. SiO₂ shows faster moisture adsorption ability in low-medium humidity (< 60% RH), while zeolite is more active at high humidity [81]. According to a study by Barbosa *et al.* [82], films based on nanochitosan and SiO₂ had more consistent antibacterial efficacy than films containing zeolite fillers, particularly after 15 days of storage. In the meantime, SiO₂ is safer for use in food applications due to its superior heat stability and reduced migration profile when compared to activated carbon [83].

Technical challenges in formulation and production

Industrial adoption of SiO₂ is still hampered by technological issues, despite its many benefits. The dispersion of particles within the polymer matrix is one of the primary limitations [84]. Agglomeration of SiO₂ nanoparticles might result in heterogeneity in the packing film and decrease the efficiency of their active surface [85]. Several strategies are employed to get

around this, including the use of surfactants or surface modification with silanes [86].

Controlling the release of active chemicals from the SiO₂ matrix is another difficulty. During processing and storage, bioactive chemicals must be encapsulated within silica pores while taking into consideration temperature, pH, polarity, and molecular size [87]. Furthermore, the release profile (release kinetics) is significantly influenced by factors including SiO₂ concentration, pore size, and loading method (physical adsorption vs. covalent bonding) [88].

From a production standpoint, to use SiO₂ in polymer films on a wide scale, the viscosity and compatibility of the molding process (casting, extrusion, and blowing) must be adjusted, and the active ingredient migration must comply with regulatory standards [89].

Case studies and quantitative data

Table 3 presents a number of recent studies that demonstrate the effectiveness of SiO₂ in various forms of active packaging applications for various types of food products. These findings generally suggest that SiO₂ is a crucial supporting element in oxidation prevention, microbial control, and ripening process regulation during storage.

According to a study by Li *et al.* [90], mesoporous silica nanoparticles (MSNs) loaded with thyme oil in a gelatin film matrix had strong antibacterial activity against *E. coli*. The potential of this approach as a substitute for artificial preservatives is demonstrated by the drop in bacterial count of > 3 log CFU/g after seven days of cold storage. MSNs serve as a carrier that preserves and releases essential oils in a regulated way, extending their antibacterial activity and preserving the stability of bioactive substances over time. Ripening management is a significant post-harvest distribution difficulty for horticulture crops like tomatoes. Alonso-Salinas *et al.* [91] used silica sachets that contained potassium permanganate (KMnO₄), a substance that effectively oxidizes ethylene, a hormone that causes fruits to mature. In order to facilitate efficient interaction with ethylene gas in the packaging headspace, SiO₂ in the form of silica gel functions as an absorbent matrix and promotes the spread of KMnO₄. As a result, tomatoes have a 5- to 7-day longer shelf life without noticeably

compromising their sensory quality. This strategy is particularly significant for export commodities and long-chain storage.

Lipid oxidation and microbiological growth are the primary factors that limit the shelf life of high-fat food goods like fish. According to Ma *et al.* [46], the usage of gelatin films treated with oregano oil and nanosilica was beneficial in preventing the growth of mold and lowering thiobarbituric acid reactive substances (TBARS) readings by as much as 50%, which indicates a decrease in fat oxidation. Antimicrobial and antioxidant active chemicals can gradually diffuse to the product surface during cold storage thanks to the protective and dispersive matrix that nanosilica provides for essential oils. Pathogenic bacteria like *Listeria monocytogenes* thrive in semi-

hard cheese products because of their high-water content and pH.

According to a study by Kalajahi *et al.* [92], the *Listeria* population may be reduced by more than 2 log CFU/g by applying a silica gel-based coating that contained zinc oxide (ZnO) and ϵ -polylysine. In this instance, silica serves as a carrier and releaser of antimicrobial active ingredients in addition to enhancing the mechanical characteristics and adherence of the cheese's protective coating. This recipe provides a natural, non-synthetic way to prolong dairy products' shelf life without changing their flavor. **Figure 4** presents representative examples of SiO₂-based active packaging systems applied to different food products, highlighting their roles in microbial control, oxidation prevention, and ripening management.

Table 3 Some key studies on the effectiveness of SiO₂ in active packaging applications.

Food products	Application forms of SiO ₂	Senyawa Aktif	Efek	Referensi
Processed chicken	Gelatin film + MSNs	Thyme oil	<i>E. coli</i> reduction > 3 log CFU/g for 7 days	Li <i>et al.</i> [87]
Fresh tomatoes	Silica sachet + KMnO ₄	Anti-ethylene	Shelf life increases by 5 - 7 days	Alonso-Salinas <i>et al.</i> [88]
Mackerel fish	Gelatin film + nanosilica	Oregano oil	Inhibits mold, decreases fat oxidation (TBARS ↓ 50%)	Ma <i>et al.</i> [46]
Semi-hard cheese	Silica gel based coating	ZnO + ϵ -polylysine	Reduction of <i>Listeria monocytogenes</i> > 2 log CFU/g	Kalajahi <i>et al.</i> [89]

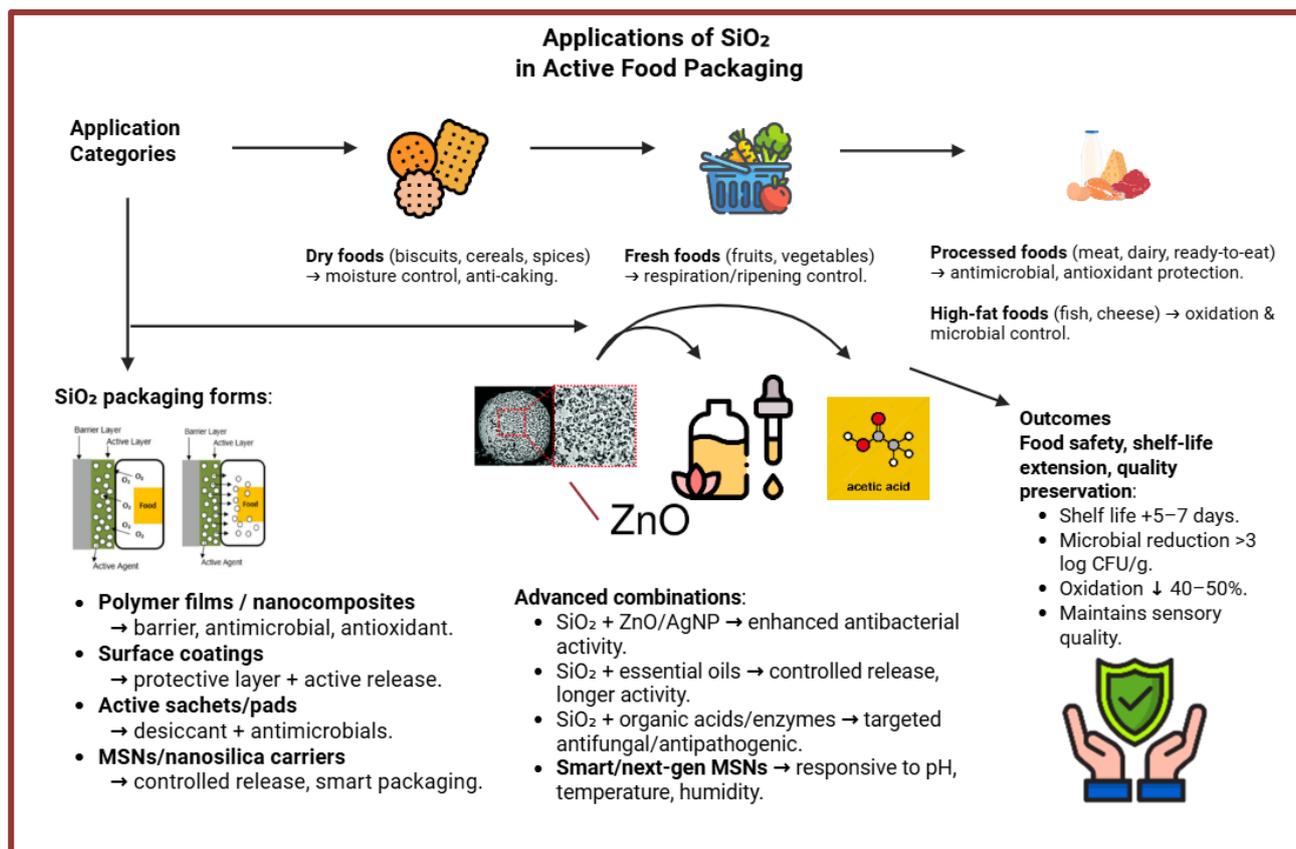


Figure 4 Applications of SiO₂-based active packaging systems in various food products through antimicrobial, antioxidant, and ripening control mechanisms.

Food regulation and safety

Several worldwide regulatory agencies strictly monitor the use of SiO₂ in active food packaging applications in order to protect consumer safety and avoid toxicological hazards brought on by chemical migration into food [93]. Even though SiO₂ has been widely accepted as safe in a variety of food formulations, a more precise and uniform risk assessment is necessary when using it in active packaging systems, especially when it comes to nanoparticle form.

Global regulations: FDA, EFSA, and BPOM

SiO₂ is a generally recognized as safe (GRAS) substance that can be used as an anti-caking agent and in food additives, according to the US Food and Drug Administration (FDA) [9]. The FDA allows SiO₂ to be used as an additive in plastic packaging for food packaging applications as long as it doesn't provide a toxicological risk to consumers and has specific migration limits.

In the European Union, SiO₂ is listed as an ingredient that is allowed in plastic food contact materials (FCM) with a specific migration limit (SML) according to regulatory framework (EU) No. 10/2011, which was issued by the European Food Safety Authority (EFSA) [8]. Although EFSA reported that amorphous silica, such as fumed silica and colloidal silica, did not exhibit acute hazardous or carcinogenic effects, additional research is still necessary to determine the bioavailability and potential tissue accumulation of nanosilica [28].

In contrast, national and international laws pertaining to food additives and packaging are referred to as BPOM in Indonesia. Packaging materials that come into direct touch with food must adhere to safety regulations and not discharge hazardous substances above the threshold, according to BPOM Regulation No. 20 of 2019 concerning Food Packaging [94]. SiO₂ is allowed in packaging, but there are currently no regulations governing its usage in nanoform; therefore, it must be examined separately and obtain special notice or authorization before being used widely [95].

Migration limits, labeling, and risk evaluation

The migration of active ingredients into food is a significant factor in the safety of SiO₂-based active packaging. The goal of migration research is to quantify the quantity of SiO₂ or similar substances that move from packaging to food when storage circumstances (temperature, duration, and food type) are reproduced [96]. For instance, the Specific Migration Limit (SML) for amorphous SiO₂ is typically non-specific because it is regarded as chemically inert, and for SiO₂ nanoparticles, some agencies, like EFSA, still take toxicological and bioaccumulation data into account before establishing a definitive SML. Both total and specific migration must be below the threshold established by the authority [28].

In addition, the labeling aspect becomes important when SiO₂ is used in active or nano form. The active system must be identified on the label, along with the fact that the packaging is not meant to be eaten or to materially alter the food's organoleptic properties [5].

Toxicology and nanotechnology issues

The use of nanosilica (SiO₂ < 100 nm) in sophisticated active packaging systems is receiving more attention, despite the fact that amorphous SiO₂ has been demonstrated to be non-toxic at typical usage dosages [97]. Numerous studies have demonstrated that when utilized in high quantities or in unstable forms, nanoparticles can induce oxidative stress, inflammation, or decreased cell function in addition to undergoing systemic translocation after consumption [98-100].

Nevertheless, a number of other investigations revealed that surface-stable and insoluble amorphous nanosilica was bioinert, did not build up in tissues, and was quickly eliminated by feces [101-104]. As a result, factors including exposure route, dispersion stability, specific surface area, morphological shape, and particle size are crucial for risk evaluation.

Various authorities advise using the precautionary principle while using nanosilica in this situation, pending the release of additional scientific data about long-term impacts [8,9,28]. In addition to migration simulations utilizing common food simulants like 10% ethanol, 3% acetic acid, or olive oil, safety

assessments should incorporate both *in vitro* and *in vivo* testing [105].

Challenges and prospects for development

SiO₂ has demonstrated considerable promise as an active element in food packaging; nonetheless, a number of technological, financial, and societal obstacles still stand in the way of its broad industrial use [106]. However, new avenues for the creation of more environmentally friendly and functional SiO₂ have been made possible by advancements in material technology and growing awareness of food sustainability.

Challenges in industrial applications

The high cost of production is one of the primary challenges, particularly for products based on nanosilica or mesoporous silica that need surface treatments, precise synthesis procedures, and extra safety testing [107]. Comparing SiO₂-based active packaging solutions to traditional packaging, the former is less cost-effective for small- and medium-sized businesses [25].

The capacity of SiO₂ to preserve its adsorptive qualities and release active ingredients (controlled release) under different storage circumstances (temperature, humidity, and pH) are issues from the functional stability perspective [108]. Its efficacy as an active agent may be impacted by the interaction between SiO₂ particles and the packaging matrix (such as bioplastic film or conventional polymer), particularly during extended storage times [11].

Additionally, there is opposition from the consumer acceptability side, particularly if information about the usage of products based on nanotechnology is not well disseminated. Even though SiO₂ has been scientifically shown safe in several evaluations, concerns about nanoparticle migration, toxicological problems, and opaque labeling can lower the degree of trust in active packaging solutions [109].

Potential for development of functional SiO₂

Advances in nanotechnology and surface engineering are enabling the development of more functional and intelligent SiO₂, such as: Smart packaging: SiO₂ can be altered to function as a gas detection sensor (ethylene, for example, for determining the ripeness of fruit) or as a pH,

temperature, and humidity indicator that indicates a drop in product quality [110].

Active biodegradable packaging: SiO₂ can be combined with biopolymer base materials such modified starch, polylactic acid (PLA), or chitosan to create packaging that is not only ecologically benign but also biodegradable and active [111].

Time-controlled or environmental-responsive release systems of antimicrobial or antioxidant agents based on mesoporous silica nanoparticles (MSNs)

enhance protection against microbial contamination and oxidative degradation [112].

This type of innovation makes it possible to expand the use of SiO₂ not only as a passive adsorbent but also as a crucial component of interactive packaging solutions that lower food waste and improve food security. The potential development of functional SiO₂ in packaging applications is illustrated in **Figure 5**.

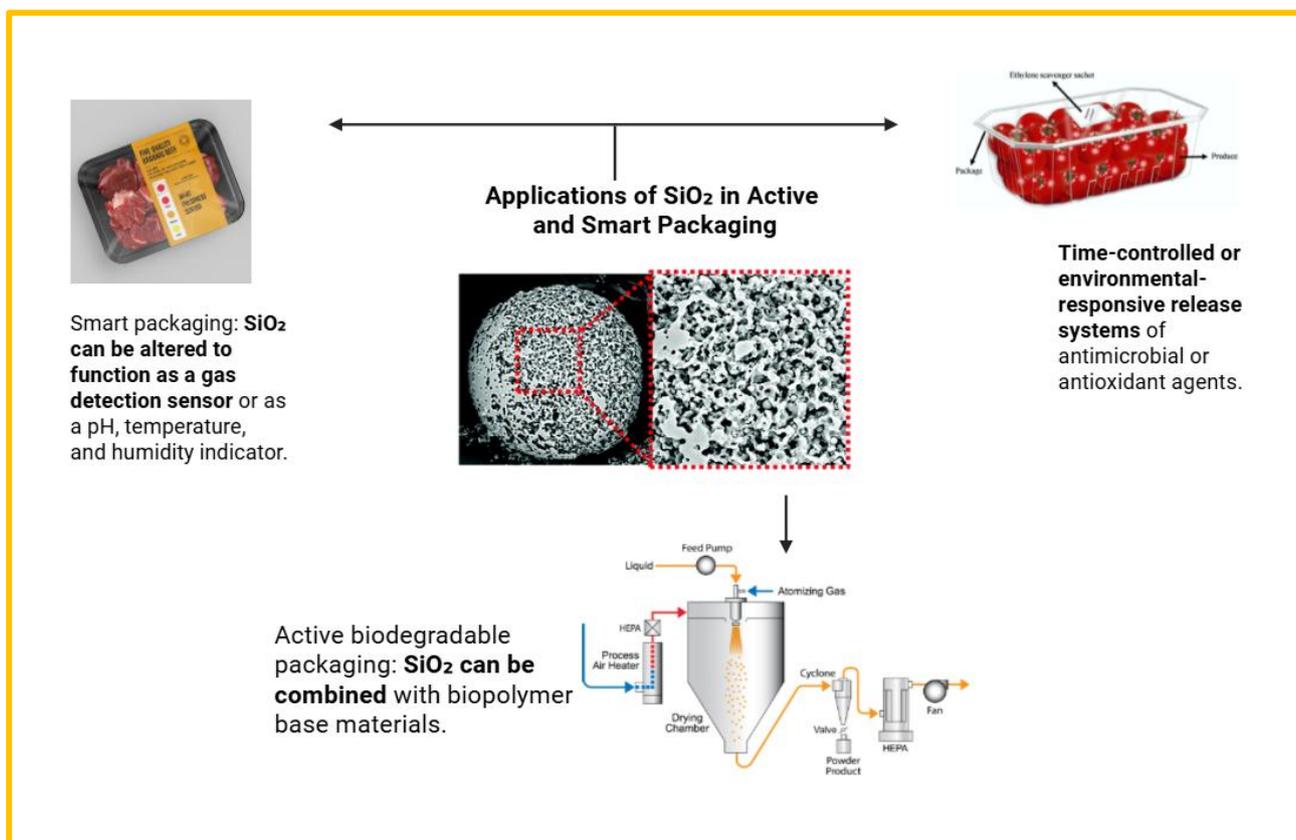


Figure 5 Potential functional development of SiO₂ in smart and active packaging applications.

The need for further research and multidisciplinary collaboration

A multidisciplinary collaborative strategy involving the disciplines of materials science, food toxicity, microbiology, chemical engineering, and consumer sociology is necessary to ensure the best possible utilization of SiO₂ in active packaging. The development of more accurate migration and biointeraction characterization techniques, particularly for nanosilica, the optimization of SiO₂ synthesis and surface modification to make it compatible with different polymer matrices, the testing of SiO₂'s

functional effectiveness under real-time storage conditions with different food types, and the investigation of consumer attitudes and public education regarding the advantages and safety of SiO₂-based active packaging should be the focus of future research.

Furthermore, a more flexible regulatory framework is required to support packaging innovations based on nanomaterials while upholding the precautionary principle of consumer safety.

Conclusions

This review shows that silicon dioxide (SiO₂) is a promising multifunctional material for active food packaging, with properties such as high surface area, strong adsorption capacity, and structural tunability that enable its role as a moisture and oxygen scavenger, carrier for antioxidants and antimicrobials, and stabilizer in nanocomposite films. Quantitative evidence demonstrates its ability to reduce microbial loads, slow lipid oxidation, and extend shelf life, making it a valuable and sustainable alternative to conventional preservatives.

The main contribution of this review is to integrate qualitative insights with quantitative data, offering a comprehensive perspective on the mechanisms, applications, and safety considerations of SiO₂ in food packaging. While challenges remain in terms of cost, toxicological concerns, and consumer acceptance, future development of functional and smart SiO₂-based packaging could enhance food safety, reduce waste, and provide significant benefits for both scientific advancement and industrial practice.

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Declaration of Generative AI in Scientific Writing

Generative AI tools were not used for scientific content, data, analysis, or conclusions. They were used only for language editing and improving grammar and clarity. All text was reviewed and approved by the authors, who take full responsibility for the manuscript.

CRedit Author Statement

Bima Putra Pratama led the conceptualization, supervision, project administration, funding acquisition, and original draft writing. **Aswin Raffi Khairullah** and **Imam Mustofa** contributed to conceptualization and draft preparation, with **Imam Mustofa** also serving as the corresponding author. **Mohammad Sukmanadi** and **Sri Mulyati** were responsible for revisions and substantive editing. **Adeyinka Oye Akintunde** and **Ilma Fauziah Ma'ruf** developed the methodology and refined the study scope. **Bantari Wisynu Kusuma Wardhani**, **Andi Thafida Khalisa**, **Dini Dwi Ludfiani**, and **Riza Zainuddin Ahmad** conducted the literature search, data curation, and visualization, including tables, with additional support from **Meta Aquarista Galia**. **Dea Anita Ariani Kurniasih** and **Arif Nur Muhammad Ansori** performed formal analysis and interpretation, while **Endo Pebri Dani Putra** and **Martasari Beti Pangestuti** further contributed through analysis, interpretation, and visualization. All authors reviewed and approved the final manuscript and agree to be accountable for all aspects of the work.

References

- [1] KG Grunert. Food quality and safety: Consumer perception and demand. *European Review of Agricultural Economics* 2005; **32(3)**, 369-391.
- [2] L Jiang, KC Seto and J Bai. Urban economic development, changes in food consumption patterns and land requirements for food production in China. *China Agricultural Economic Review* 2015; **7(2)**, 240-261.
- [3] S Karanth, S Feng, D Patra and AK Pradhan. Linking microbial contamination to food spoilage and food waste: The role of smart packaging, spoilage risk assessments, and date labeling. *Frontiers in Microbiology* 2023; **14(1)**, 1198124.
- [4] MW Ahmed, MA Haque, M Mohibullah, MSI Khan, MA Islam, MHT Mondal and R Ahmmed.

- A review on active packaging for quality and safety of foods: Current trends, applications, prospects and challenges. *Food Packaging and Shelf Life* 2022; **33(1)**, 100913.
- [5] R Chawla, S Sivakumar and H Kaur. Antimicrobial edible films in food packaging: Current scenario and recent nanotechnological advancements - a review. *Carbohydrate Polymer Technologies and Applications* 2021; **2(1)**, 100024.
- [6] PU Nzereogu, AD Omah, FI Ezema, EI Iwuoha and AC Nwanya. Silica extraction from rice husk: Comprehensive review and applications. *Hybrid Advances* 2023; **4(1)**, 100111.
- [7] M Vallet-Regí and F Balas. Silica materials for medical applications. *Open Biomedical Engineering Journal* 2008; **2(1)**, 1-9.
- [8] M Younes, P Aggett, F Aguilar, R Crebelli, B Dusemund, M Filipič, MJ Frutos, P Galtier, D Gott, U Gundert-Remy, GG Kuhnle, JC Leblanc, IT Lillegaard, P Moldeus, A Mortensen, A Oskarsson, I Stankovic, I Waalkens-Berendsen, RA Woutersen, ..., C Lambré. Re-evaluation of silicon dioxide (E 551) as a food additive. *EFSA Journal* 2018; **16(1)**, e05088.
- [9] Food and Drug Administration. *Analysis of silicon dioxide food additives*. Food and Drug Administration, Maryland, United States, 2023.
- [10] VS Shankar, G Velmurugan, DE Raja, T Manikandan, SS Kumar, J Singh, M Nagaraj and AJP Kumar. A review on the development of silicon and silica based nano materials in the food industry. *Silicon* 2024; **16(1)**, 979-988.
- [11] W Zhang, H Ahari, Z Zhang and SM Jafari. Role of silica (SiO₂) nano/micro-particles in the functionality of degradable packaging films/coatings and their application in food preservation. *Trends in Food Science & Technology* 2023; **133(1)**, 75-86.
- [12] K Trzeciak, A Chotera-Ouda, II Bak-Sypien and MJ Potrzebowski. Mesoporous silica particles as drug delivery systems-the state of the art in loading methods and the recent progress in analytical techniques for monitoring these processes. *Pharmaceutics* 2021; **13(7)**, 950.
- [13] KY Perera, AK Jaiswal and S Jaiswal. Biopolymer-based sustainable food packaging materials: Challenges, solutions, and applications. *Foods* 2023; **12(12)**, 2422.
- [14] JJ Petkowski, W Bains and S Seager. On the potential of silicon as a building block for life. *Life* 2020; **10(6)**, 84.
- [15] DA Zamiatina, DA Zamyatin, GB Mikhalevskii and NS Chebikin. Silica polymorphs formation in the jänisjärvi impact structure: Tridymite, cristobalite, quartz, trace stishovite and coesite. *Minerals* 2023; **13(5)**, 686.
- [16] IF Myronyuk, VO Kotsyubynsky, TV Dmytrotsa, LM Soltys and VM Gun'ko. Atomic structure and morphology of fumed silica. *Physics and Chemistry of Solid State* 2020; **21(2)**, 325-331.
- [17] FD Agrippina, M Ismayati, S Hidayati and BP Pratama. Utilization of tannins with various polymers for green-based active packaging: A review. *Jurnal Sylva Lestari* 2024; **12(3)**, 893.
- [18] Misgiati, I Winarni, T Murniasih, E Novriyanti, K Tarman, M Safithri, I Setyaningsih, D Cahyati, BP Pratama and I Wirawati. The anticancer and antioxidant potential of local sea cucumber *Holothuria edulis*, an ecology balancer of Labuan Bajo marine ecosystem. *Case Studies in Chemical and Environmental Engineering* 2024; **9**, 100625.
- [19] E Febriana, W Mayangsari, S D Yudianto, E Sulistiyono, M Handayani, F Firdiyono, A Maksum, AB Prasetyo and JW Soedarsono. Novel method for minimizing reactant in the synthesis of sodium silicate solution from mixed-phase quartz-amorphous SiO₂. *Case Studies in Chemical and Environmental Engineering* 2024; **9(1)**, 100656.
- [20] M Riza, I Zuwana, Nuraini, AE Mawarni, SD Said, Mukhlisien and R Dewi. Biocomposite film properties of whey protein isolate/PVA-silica. *Results in Engineering* 2025; **26(1)**, 104514.
- [21] V Khavryutchenko, AI Khavryutchenko and H Barthel. Fumed silica synthesis: Influence of small molecules on the particle formation process. *Macromolecular Symposia* 2001; **169(1)**, 1-6.
- [22] VD Khavryuchenko, OV Khavryuchenko and VV Lisnya. Formation of pyrogenic silica: Spectroscopic and quantum chemical insight.

- Critical Reviews in Solid State and Materials Sciences* 2011; **36(2)**, 47-65.
- [23] ZA ALOthman. A review: Fundamental aspects of silicate mesoporous materials. *Materials* 2012; **5(12)**, 2874-2902.
- [24] T Hou, S Ma, F Wang and L Wang. A comprehensive review of intelligent controlled release antimicrobial packaging in food preservation. *Food Science and Biotechnology* 2023; **32(11)**, 1459-1478.
- [25] I Hamidu, B Afotey, B Kwakye-Awuah and DA Anang. Synthesis of silica and silicon from rice husk feedstock: A review. *Heliyon* 2025; **11(4)**, e42491.
- [26] R Rani, P Malik, S Dhanial and TK Mukherjee. Recent advances in mesoporous silica nanoparticle-mediated drug delivery for breast cancer treatment. *Pharmaceutics* 2023; **15(1)**, 227.
- [27] Y Yang, JJ Faust, J Schoepf, K Hristovski, DG Capco, P Herckes and P Westerhoff. Survey of food-grade silica dioxide nanomaterial occurrence, characterization, human gut impacts and fate across its lifecycle. *Science of the Total Environment* 2016; **565(1)**, 902-912.
- [28] EFSA Panel on Food Additives and Flavourings (FAF), M Younes, G Aquilina, L Castle, G Degen, KH Engel, P Fowler, MJF Fernandez, P Fürst, R Gürtler, T Husøy, M Manco, W Mennes, P Moldeus, S Passamonti, R Shah, I Waalkens-Berendsen, M Wright, C Andreoli, ..., U Gundert-Remy. Re-evaluation of silicon dioxide (E 551) as a food additive in foods for infants below 16 weeks of age and follow-up of its re-evaluation as a food additive for uses in foods for all population groups. *EFSA Journal* 2024; **22(10)**, e8880.
- [29] Food and Drug Administration. Generally Recognized as Safe (GRAS), Available at: <https://www.fda.gov/food/food-ingredients-packaging/generally-recognized-safe-gras>, accessed May 2025.
- [30] X Dong, Z Wu, X Li, L Xiao, M Yang, Y Li, J Duan and Z Sun. the size-dependent cytotoxicity of amorphous silica nanoparticles: A systematic review of *in vitro* studies. *International Journal of Nanomedicine* 2020; **15(1)**, 9089-9113.
- [31] IY Kim, E Joachim, H Choi and K Kim. Toxicity of silica nanoparticles depends on size, dose, and cell type. *Nanomedicine* 2015; **11(6)**, 1407-1416.
- [32] Organisation for Economic Co-operation and Development. *OECD guidelines for the testing of chemicals: Section on nanomaterials*. OECD Publishing, Paris, France, 2021.
- [33] EFSA Scientific Committee, A Hardy, D Benford, T Halldorsson, MJ Jeger, HK Knutsen, S More, H Naegeli, H Noteborn, C Ockleford, A Ricci, G Rychen, JR Schlatter, V Silano, R Solecki, D Turck, M Younes, Q Chaudhry, F Cubadda, ..., A Mortensen. Guidance on risk assessment of the application of nanoscience and nanotechnologies in the food and feed chain: Part 1, human and animal health. *EFSA Journal* 2018; **16(7)**, e05327.
- [34] V Mankad and PK Jha. First-principles study of water adsorption on α -SiO₂ [110] surface. *AIP Advances* 2016; **6(1)**, 085001.
- [35] JT Yates. Water interactions with silica surfaces: A big role for surface structure. *Surface Science* 2004; **565(2-3)**, 103-106.
- [36] PP Ziemiański, M Cherotich, I Sadykov, C Mansour, I Lunati, M Ranocchiaro, WJ Malfait and S Galmarini. Hydrophobic silica gels and aerogels for direct air capture: Hybrid grafting to suppress water uptake and capillary condensation. *ACS Applied Materials & Interfaces* 2025; **17(30)**, 42954-42968.
- [37] Y Yao, C Liu, W Xiong, Q Liang, P Xuan, X Zeng, S Zeng, Q Zhou and F Huang. Silicon dioxide as an efficient adsorbent in the degumming of rapeseed oil. *Journal of Cleaner Production* 2020; **268(1)**, 122344.
- [38] KK Qian and RH Bogner. Application of mesoporous silicon dioxide and silicate in oral amorphous drug delivery systems. *Journal of Pharmaceutical Sciences* 2012; **101(2)**, 444-463.
- [39] X Xu, A Liu, S Hu, I Ares, MR Martínez-Larrañaga, X Wang, M Martínez, A Anadón and MA Martínez. Synthetic phenolic antioxidants: Metabolism, hazards and mechanism of action. *Food Chemistry* 2021; **353(1)**, 129488.
- [40] A Rezagholizade-Shirvan, M Soltani, S Shokri, R Radfar, M Arab and E Shamloo. Bioactive compound encapsulation: Characteristics,

- applications in food systems, and implications for human health. *Food Chemistry: X* 2024; **24(1)**, 101953.
- [41] GD Jovanovic, AS Klaus and MP Niksic. Antimicrobial activity of chitosan films with essential oils against *Listeria monocytogenes* on cabbage. *Jundishapur Journal of Microbiology* 2016; **9(9)**, e34804.
- [42] FMR Khani, M Naseri, S Babaei, SMH Hosseini and S Valizadeh. Cumin essential oil-infused chitosan-PVA composite coatings: An innovative approach for developing antimicrobial, antioxidant and functionalized polyethylene films. *International Journal of Biological Macromolecules* 2025; **322(Part 2)**, 145270.
- [43] J Zhao, J Qian, J Luo, M Huang, W Yan and J Zhang. Application of Ag@SiO₂ nanoparticles within PVA to reduce growth of *E. coli* and *S. aureus* in beef patties. *Journal of Food Science* 2022; **87(10)**, 4569-4579.
- [44] A Ayala, MF Muñoz and S Argüelles. Lipid peroxidation: Production, metabolism, and signaling mechanisms of malondialdehyde and 4-hydroxy-2-nonenal. *Oxidative Medicine and Cellular Longevity* 2014; **2014(1)**, 360438.
- [45] H Pulikkalparambil, D Phothisarattana, K Promhuad and N Harnkarnsujarit. Effect of silicon dioxide nanoparticle on microstructure, mechanical and barrier properties of biodegradable PBAT/PBS food packaging. *Food Bioscience* 2023; **55(1)**, 103023.
- [46] N Chanka, W Donphai, M Chareonpanich, K Faungnawakij, G Rupprechter and A Seubsai. Potassium permanganate-impregnated amorphous silica-alumina derived from sugar cane bagasse ash as an ethylene scavenger for extending shelf life of mango fruits. *ACS Omega* 2024; **9(6)**, 6749-9760.
- [47] S Ribes, M Ruiz-Rico, É Pérez-Esteve, A Fuentes, P Talens, R Martínez-Mañez and JM Barat. Eugenol and thymol immobilised on mesoporous silica-based material as an innovative antifungal system: Application in strawberry jam. *Food Control* 2017; **81(1)**, 181-188.
- [48] Y Ma, S Chen, P Liu, Y He, F Chen, Y Cai and X Yang. Gelatin improves the performance of oregano essential oil nanoparticle composite films - application to the preservation of mullet. *Foods* 2023; **12(13)**, 2542.
- [49] M Hadidi, R Liñán-Atero, M Tarahi, MC Christodoulou and F Aghababaei. The potential health benefits of gallic acid: Therapeutic and food applications. *Antioxidants* 2024; **13(8)**, 1001.
- [50] E Warsiki. Application of chitosan as biomaterial for active packaging of ethylene absorber. *IOP Conference Series: Earth and Environmental Science* 2018; **141(1)**, 012036.
- [51] Y Jiang, Y Zhang and Y Deng. Latest advances in active materials for food packaging and their application. *Foods* 2023; **12(22)**, 4055.
- [52] Z Guo, NJ Martucci, Y Liu, E Yoo, E Tako and GJ Mahler. Silicon dioxide nanoparticle exposure affects small intestine function in an in vitro model. *Nanotoxicology* 2018; **12(5)**, 485-508.
- [53] H San, Y Laurenza, E Behzadfar, U Sonchaeng, K Wadaugsorn, J Sodsai, T Kaewpetch, K Promhuad, A Srisa, P Wongphan and N Harnkarnsujarit. Functional polymer and packaging technology for bakery products. *Polymers* 2022; **14(18)**, 3793.
- [54] A Sridhar, M Ponnuchamy, PS Kumar and A Kapoor. Food preservation techniques and nanotechnology for increased shelf life of fruits, vegetables, beverages and spices: A review. *Environmental Chemistry Letters* 2021; **19(2)**, 1715-1735.
- [55] A Duda-Chodak, T Tarko and K Petka-Poniatowska. Antimicrobial compounds in food packaging. *International Journal of Molecular Sciences* 2023; **24(3)**, 2457.
- [56] R Zhou, H Ma, Z Zhou, W Xu, F Ren and C Li. Preparation of SiO₂ particles with silicone-methoxy groups on surface and its co-curing hydroxyl silicone oil. *Materials Research Express* 2020; **7(1)**, 065309.
- [57] F Bi, X Zhang, J Liu, H Yong, L Gao and J Liu. Development of antioxidant and antimicrobial packaging films based on chitosan, D- α -tocopheryl polyethylene glycol 1000 succinate and silicon dioxide nanoparticles. *Food Packaging and Shelf Life* 2020; **24(1)**, 100503.

- [58] FE Williams, AK Lee, S Orandi and DM Lewis. Antibacterial action of functional silicon dioxide: An investigation of the attachment and separation of bacteria. *Environmental Technology* 2018; **41(6)**, 703-710.
- [59] E Drago, R Campardelli, M Pettinato and P Perego. Innovations in smart packaging concepts for food: An extensive review. *Foods* 2020; **9(11)**, 1628.
- [60] FL Sousa, M Santos, SM Rocha and T Trindade. Encapsulation of essential oils in SiO₂ microcapsules and release behaviour of volatile compounds. *Journal of Microencapsulation* 2014; **31(7)**, 627-635.
- [61] BP Pratama, Y Pranoto, Supriyadi and RT Swasono. The identification of β -ocimene biosynthetic pathway through mevalonate acid (MVA) and 1-deoxy-D-xylulose 5-phosphate (DXP) pathways using crude enzyme extracts in Indonesian bay leaf (*Syzygium polyanthum*). *Tropical Life Sciences Research* 2022; **33(2)**, 1-17.
- [62] L Wang, C Hu and L Shao. The antimicrobial activity of nanoparticles: Present situation and prospects for the future. *International Journal of Nanomedicine* 2017; **12(1)**, 1227-1249.
- [63] C Shuai, F Yang, Y Shuai, S Peng, S Chen, Y Deng and P Feng. Silicon dioxide nanoparticles decorated on graphene oxide nanosheets and their application in poly(l-lactic acid) scaffold. *Journal of Advanced Research* 2023; **48(1)**, 175-190.
- [64] A Pugazhendhi, S Vasantharaj, S Sathiyavimal, RK Raja, I Karuppusamy, M Narayanan, S Kandasamy and K Brindhadevi. Organic and inorganic nanomaterial coatings for the prevention of microbial growth and infections on biotic and abiotic surfaces. *Surface and Coatings Technology* 2021; **425(1)**, 127739.
- [65] R Fatima, P Katiyar and K Kushwaha. Recent advances in mesoporous silica nanoparticle: Synthesis, drug loading, release mechanisms, and diverse applications. *Frontiers in Nanotechnology* 2025; **7(1)**, 1564188.
- [66] P Uniyal, P Gaur, J Yadav, NA Bhalla, T Khan, H Junaedi and TA Sebaey. A comprehensive review on the role of nanosilica as a toughening agent for enhanced epoxy composites for aerospace applications. *ACS Omega* 2025; **10(16)**, 15810-15839.
- [67] M Vallet-Regí, F Schüth, D Lozano, M Colilla and M Manzano. Engineering mesoporous silica nanoparticles for drug delivery: where are we after 2 decades? *Chemical Society Reviews* 2022; **51(13)**, 5365-5451.
- [68] A Budiman, A Rusdin, YW Wardhana, LE Puluhulawa, FRC Mo'o, N Thomas, AM Gazzali and DL Aulifa. Exploring the transformative potential of functionalized mesoporous silica in enhancing antioxidant activity: A comprehensive review. *Antioxidants* 2024; **13(8)**, 936.
- [69] S Loganathan, J Jacob, RB Valapa and S Thomas. Influence of linear and branched amine functionalization in mesoporous silica on the thermal, mechanical and barrier properties of sustainable poly(lactic acid) biocomposite films. *Polymer* 2018; **148(1)**, 149-157.
- [70] R Zende, V Ghase and V Jamdar. Recent advances in the antimicrobial and antioxidant capabilities of PLA based active food packaging. *Polymer-Plastics Technology and Materials* 2024; **64(4)**, 439-464.
- [71] RA Jacinto-Valderrama, CT Andrade, M Pateiro, JM Lorenzo and CA Conte-Junior. Recent Trends in active packaging using nanotechnology to inhibit oxidation and microbiological growth in muscle foods. *Foods* 2023; **12(19)**, 3662.
- [72] R Ordoñez, L Atarés and A Chiralt. Properties of PLA films with cinnamic acid: Effect of the processing method. *Food and Bioproducts Processing* 2022; **133(1)**, 25-33.
- [73] A John, KP Črešnar, DN Bikiaris and LF Zemljič. Colloidal solutions as advanced coatings for active packaging development: Focus on PLA systems. *Polymers* 2023; **15(2)**, 273.
- [74] R Sami, E Khojah, A Elhakem, N Benajiba, M Helal, N Alhuthal, SA Alzahrani, M Alharbi and M Chavali. Performance study of nano/SiO₂ films and the antimicrobial application on cantaloupe fruit shelf-life. *Applied Sciences* 2021; **11(1)**, 3879.
- [75] M Gao, Q Ma, Q Lin, J Chang and H Ma. A novel approach to extract SiO₂ from fly ash and its considerable adsorption properties. *Materials & Design* 2017; **116(1)**, 666-675.

- [76] S Baytak, AR Türker and BS Cevrimli. Application of silica gel 60 loaded with *Aspergillus niger* as a solid phase extractor for the separation/preconcentration of chromium(III), copper(II), zinc(II), and cadmium(II). *Journal of Separation Science* 2005; **28(18)**, 2482-2488.
- [77] B Tessema, G Gonfa, SM Hailegiorgis, GA Workneh and TG Tadesse. Synthesis and evaluation of the anti-bacterial effect of modified silica gel supported silver nanoparticles on *E. coli* and *S. aureus*. *Results in Chemistry* 2024; **7(1)**, 101471.
- [78] V Selvarajan, S Obuobi and PLR Ee. Silica nanoparticles-a versatile tool for the treatment of bacterial infections. *Frontiers in Chemistry* 2020; **8(1)**, 602.
- [79] W Lu, R Cui, B Zhu, Y Qin, G Cheng, L Li and M Yuan. Influence of clove essential oil immobilized in mesoporous silica nanoparticles on the functional properties of poly(lactic acid) biocomposite food packaging film. *Journal of Materials Research and Technology* 2021; **11(1)**, 1152-1161.
- [80] H Onyeaka, P Passaretti, T Miri and ZT Al-Sharify. The safety of nanomaterials in food production and packaging. *Current Research in Food Science* 2022; **5(1)**, 763-774.
- [81] A Al Ezzi, L Ismael, MA Fayad, AA Jaber, AM Al Jubori, T Al-Jadir, HA Dhahad, H Ma and T Yusaf. Experimental investigation of dehumidification and regeneration of zeolite coated energy exchanger. *International Journal of Thermofluids* 2022; **15(1)**, 100164.
- [82] GP Barbosa, HS Debone, P Severino, EB Souto and CF da Silva. Design and characterization of chitosan/zeolite composite films - Effect of zeolite type and zeolite dose on the film properties. *Materials Science and Engineering: C* 2016; **60(1)**, 246-254.
- [83] Y Yao, C Liu, W Xiong, Q Liang, P Xuan, X Zeng, S Zeng, Q Zhou and F Huang. Silicon dioxide as an efficient adsorbent in the degumming of rapeseed oil. *Journal of Cleaner Production* 2020; **268(1)**, 122344.
- [84] AM Al-Thobity and MM Gad. Effect of silicon dioxide nanoparticles on the flexural strength of heat-polymerized acrylic denture base material: A systematic review and meta-analysis. *The Saudi Dental Journal* 2021; **33(8)**, 775-783.
- [85] Z Torabi and AM Nafchi. The effects of SiO₂ nanoparticles on mechanical and physicochemical properties of potato starch films. *Journal of Chemical Health Risks* 2013; **3(1)**, 33-42.
- [86] A Kumar, S Negi and S Kar. A study on functionalization process of silicon dioxide nanoparticles for hydrophobic coating applications. *Surface and Interface Analysis* 2024; **56(7)**, 447-455.
- [87] R Domínguez, M Pateiro, PES Munekata, DJ McClements and JM Lorenzo. Encapsulation of bioactive phytochemicals in plant-based matrices and application as additives in meat and meat products. *Molecules* 2021; **26(13)**, 3984.
- [88] AH Khalbas, TM Albayati, NS Ali and IK Salih. Drug loading methods and kinetic release models using of mesoporous silica nanoparticles as a drug delivery system: A review. *South African Journal of Chemical Engineering* 2024; **50(1)**, 261-280.
- [89] WJ Mitchell, BJ Thibeault, DD John and TE Reynolds. Highly selective and vertical etch of silicon dioxide using ruthenium films as an etch mask. *Journal of Vacuum Science & Technology A* 2021; **39(4)**, 043204.
- [90] S Li, C Du, M Zhai, J Sheng and Y Song. Enhanced effect of ultrasound and gelatin on physical and antibacterial properties of thymol/hollow mesoporous silicon spheres doped zein film. *Food Bioscience* 2024; **60(1)**, 104440.
- [91] R Alonso-Salinas, S López-Miranda, AJ Pérez-López, L Noguera-Artiaga, ÁA Carbonell-Barrachina, E Núñez-Delicado and JR Acosta-Motos. Novel combination of ethylene oxidisers to delay losses on postharvest quality, volatile compounds and sensorial analysis of tomato fruit. *LWT* 2022; **170(1)**, 114054.
- [92] NJ Kalajahi, B Ghanbarzadeh, J Dehghannya and A Ostadrahimi. The physicomechanical optimization and antimicrobial properties of the ϵ -polylysine/ZnO nanoparticles loaded active packaging films. *Food and Humanity* 2024; **3(1)**, 100401.

- [93] N Seref and G Cufaoglu. Food packaging and chemical migration: A food safety perspective. *Journal of Food Science* 2025; **90(5)**, e70265.
- [94] Badan Pengawas Obat dan Makanan Republik Indonesia. Peraturan Badan POM Nomor 20 Tahun 2019 tentang Kemasan Pangan, Available at <https://standarpangan.pom.go.id>, accessed May 2025.
- [95] EFSA Panel on Food Contact Material. Enzymes and flavourings and processing aids (CEF). Statement on the safety assessment of the substance silicon dioxide, silanated, FCM Substance No 87 for use in food contact materials. *EFSA Journal* 2014; **12(6)**, 3712.
- [96] RK Gupta, S Pipliya, S Karunanithi, UGM Eswaran, S Kumar, S Mandliya, PP Srivastav, T Suthar, AM Shaikh, E Harsányi and B Kovács. Migration of chemical compounds from packaging materials into packaged foods: Interaction, mechanism, assessment, and regulations. *Foods* 2024; **13(19)**, 3125.
- [97] X Yang, J Liu, H He, L Zhou, C Gong, X Wang, L Yang, J Yuan, H Huang, L He, B Zhang and Z Zhuang. SiO₂ nanoparticles induce cytotoxicity and protein expression alteration in HaCaT cells. *Particle and Fibre Toxicology* 2010; **7(1)**, 1.
- [98] A Mendoza, JA Torres-Hernandez, JG Ault, JH Pedersen-Lane, D Gao and DA Lawrence. Silica nanoparticles induce oxidative stress and inflammation of human peripheral blood mononuclear cells. *Cell Stress and Chaperones* 2014; **19(6)**, 777-790.
- [99] M Kusaczuk, R Krętowski, M Naumowicz, A Stypułkowska and M Cechowska-Pasko. Silica nanoparticle-induced oxidative stress and mitochondrial damage is followed by activation of intrinsic apoptosis pathway in glioblastoma cells. *International Journal of Nanomedicine* 2018; **13(1)**, 2279-2294.
- [100] M Horie, K Nishio, H Kato, S Endoh, K Fujita, A Nakamura, Y Hagihara, Y Yoshida and H Iwahashi. Evaluation of cellular effects of silicon dioxide nanoparticles. *Toxicology Mechanisms and Methods* 2014; **24(3)**, 196-203.
- [101] P Singh, S Srivastava and SK Singh. Nanosilica: Recent progress in synthesis, functionalization, biocompatibility, and biomedical applications. *ACS Biomaterials Science & Engineering* 2019; **5(10)**, 4882-4898.
- [102] N Waegeneers, A Brasseur, E Van Doren, S Van der Heyden, PJ Serreyn, L Pussemier, J Mast, YJ Schneider, A Ruttens and S Roels. Short-term biodistribution and clearance of intravenously administered silica nanoparticles. *Toxicology Reports* 2018; **5(1)**, 632-638.
- [103] MG Bianchi, M Chiu, G Taurino, E Bergamaschi, F Turrone, L Mancabelli, G Longhi, M Ventura and O Bussolati. Amorphous silica nanoparticles and the human gut microbiota: A relationship with multiple implications. *Journal of Nanobiotechnology* 2024; **22(1)**, 45.
- [104] N Sharma and S Jha. Amorphous nanosilica induced toxicity, inflammation and innate immune responses: A critical review. *Toxicology* 2020; **441(1)**, 152519.
- [105] D Enescu, A Dehelean, C Gonçalves, MA Cerqueira, DA Magdas, P Fucinos and LM Pastrana. Evaluation of the specific migration according to EU standards of titanium from Chitosan/Metal complexes films containing TiO₂ particles into different food simulants. A comparative study of the nano-sized vs micro-sized particles. *Food Packaging and Shelf Life* 2020; **26(1)**, 100579.
- [106] M Firouzamandi, M Hejazy, A Mohammadi, AA Shahbazfar and R Norouzi. *In vivo* toxicity of oral administrated nano-SiO₂: Can food additives increase apoptosis? *Biological Trace Element Research* 2023; **201(10)**, 4769-4778.
- [107] B Xu, S Li, R Shi and H Liu. Multifunctional mesoporous silica nanoparticles for biomedical applications. *Signal Transduction and Targeted Therapy* 2023; **8(1)**, 435.
- [108] S Banivaheb, S Dan, H Hashemipour and M Kalantari. Synthesis of modified chitosan TiO₂ and SiO₂ hydrogel nanocomposites for cadmium removal. *Journal of Saudi Chemical Society* 2021; **25(8)**, 101283.
- [109] X Ma, Y Tian, R Yang, H Wang, LW Allahou, J Chang, G Williams, JC Knowles and A Poma. Nanotechnology in healthcare, and its safety and environmental risks. *Journal of Nanobiotechnology* 2024; **22(1)**, 715.

- [110]M Ma, X Yang, X Ying, C Shi, Z Jia and B Jia. Applications of gas sensing in food quality detection: A review. *Foods* 2023; **12(21)**, 3966.
- [111]MY Khalid and ZU Arif. Novel biopolymer-based sustainable composites for food packaging applications: A narrative review. *Food Packaging and Shelf Life* 2022; **33(1)**, 100892.
- [112]GC Carvalho, RM Sábio, T de Cássia Ribeiro, AS Monteiro, DV Pereira, SJL Ribeiro and M Chorilli. Highlights in mesoporous silica nanoparticles as a multifunctional controlled drug delivery nanoplatform for infectious diseases treatment. *Pharmaceutical Research* 2020; **37(10)**, 191.