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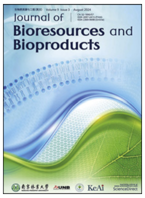

Review

Recent antibacterial agents from biomass derivatives: Characteristics and applications

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ABSTRACT

Enhancing awareness of personal cleanliness and antibacterial resistance has intensified the antibacterial substance request on consumable products. Antibacterial agents that have been commercialized nowadays are produced from inorganic and non-renewable substances. This provides several drawbacks, particularly against health and environmental issues. Therefore, many scientists work on substituting fossil-fuel-based antibacterial agents with natural ones such as from biomass. Biomass derivatives, natural abundances of biopolymers in the world, amount to major compounds including polysaccharides (cellulose, hemicellulose, and chitosan) and polyphenol (tannin and lignin) substances which are capable to combat the growth of Gram-positive bacteria and Gram-negative bacteria. To date, no report focuses on a deep understanding of antibacterial properties derived from biomass and the internal and external factors effects. This work provides that gap because comprehensive knowledge is necessary before applying biomass to the products. The potency of biomass derivatives as antibacterial additives is also summarized. Basic knowledge of antibacterial characteristics to the application in products is highlighted in this review. Besides, the discussion about challenges and future perspectives is also delivered.

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1. Introduction

Antibacterial resistance is among the most pressing issues in the recent past. The World Health Organisation identifies bacterial resistance as a severe global issue (Jardine and Sayed, 2018). Therefore, antibacterial consumption was forecast to be 99 502 tons (95 % coincident index: 68 535−198 052) in 2020 and is expected to rise to 107 472 tons (95 % coincident index: 75 927−202 661) by 2030 based on recent advances (Mulchandani et al., 2023) with mostly for cosmetics, healthcare, food processing sector, and textile (Transparency-Market-Research, 2020). Novel antibacterial compounds have been invented to combat this; nevertheless, the mode of action and ecological impact of these antibacterials must be considered (Jardine and Sayed, 2018).

Metal or metal oxide nanoparticles are frequently utilized as antibacterial agents due to impressive antibacterial characteristics toward both Gram-negative and Gram-positive bacteria, larger surface area, and high stability (Park et al., 2013; Purwanti et al., 2021; Zhang et al., 2022). Because of the harmful impact of some synthetic preservatives on consumer health, additional studies are being conducted to determine the possibility of natural antimicrobials to meet customer safety laws. Therefore, the research for natural antibacterial agents to replace synthetic chemicals is predicted to rise significantly (Gyawali and Ibrahim, 2014). Natural biopolymers generated from biomass derivatives (both wood and nonwoody biomass) have promising antibacterial properties (Lobo et al., 2021). They might contain alkaloids, flavonoids, tannins, and other phytochemical components that serve as defense mechanisms against different microorganisms. These compounds may have antifungal, antibacterial, antioxidant, anticancer, and other effects (Jabborova et al., 2019).

Biomass consists of components originating from living materials which include plants (agriculture) and animals (land and marine animals). The abundance of biomass waste worldwide has urged for solutions to convert the waste into valuable useful products. In several industries, biomass materials have been postulated as a possible replacement for current typical chemical materials due to their benign and renewable features (Brun et al., 2017). Biomass waste has been found to contain useful components or bioactive compounds that can be further used for several valorizations. The current trend for achieving a circular economy targets the elimination of waste including biowaste (zero waste cycle) by inventing holistic systems considering the entire product lifecycle (Karimah et al., 2021; Orejuela-Escobar et al., 2021). The assurance of biomass derivatives providing low raw material cost and high sustainability led to rigorous environmentally friendly product development to achieve a green future. One of the promising applications of biomass derivatives (lignin, tannin, cellulose, hemicellulose, chitosan, etc.) is to be applied as an antibacterial agent against Gram-positive bacteria and Gram-negative bacteria (Lobo et al., 2021; Bao et al., 2022; Villanueva et al., 2022; Hidayat et al., 2023). However, the antibacterial activity relies on the source, functionalization, isolation, and types of bacteria (Yang et al., 2016; Alzagameem et al., 2019; Nemeş et al., 2022).

Understanding each characteristic of biomass compounds is an essential strategy before further utilization. Lobo et al. (2021) overviewed the potency of lignocellulosic material as an antimicrobial agent. However, currently, no comprehensive report has been found on biomass derivatives' capability as antibacterial agents from a fundamental aspect until the application. The science behind antibacterial characteristics from biomass and its influence factor is an essential primary step before considering the products. Therefore, this article emphasized the recent development in the potency of biomass compounds (lignin, tannin, cellulose, hemicellulose, and chitosan) as antibacterial agents according to the source, chemical modification, types of bacteria, inhibition mechanism, and eventually the suitable application on products. Through this summary, scientists can easily find the research gap on valorization biomass as an antibacterial additive based on recent research. Challenges and future perspectives are also suggested to spark ideas from scientists and industries.

2. Current trend antibacterial agent from biomass

Agriculture biomass is built from hemicellulose, cellulose, tannin, and lignin as the main components building up the biomass structure. Besides, other biomass wastes such as crustaceans, fungi, seaweed, and yeast consist of chitosan/chitin as a main component besides cellulose. According to the Scopus website on August 10th 2023, there were 737 publications on the keyword "biomass as antibacterial agent" since the last decade. The trend number of publications in 2013-2023 is available in Fig. 1a while its visualization by VOSviewer of these research papers is shown in Fig. 1b. In general, the trend of publication on evaluating the potency of biomass as an antibacterial agent gradually upsurges every year. The visualization (Fig. 1b) showed that as the dot size and color are higher and brighter, the higher the occurrence of those keywords is. In Fig. 1b, many papers work on the use of biomass as a bacterial inhibitor in biofilm which is usually used in food packaging. Meanwhile, mainly the activity was tested on *Staphylococcus aureus* (*S. aureus*) (Gram-positive bacteria). The antibacterial agent is applied in many sectors such as cosmetics, dental, food, textile, drug, household products, and biomedical products (Blessy Rebecca et al., 2022; Bose et al., 2023).

Interestingly, many works reported how to combine biomass derivatives with silver nanoparticles (AgNPs) to boost antibacterial activity because AgNPs had bright dots. Scandorieiro et al. (2023) found the combination of oregano derivatives with AgNPs improved the antibiofilm effect against *Klebsiella pneumoniae* (*K. pneumoniae*) and *Escherichia coli* (*E. coli*). In another report by Wolny-Koładka et al. (2022), biomass from plant waste was utilized for the biosynthesize of AgNPs to be used as one of the ingredients in cleaning and disinfection formulations. Due to the COVID-19 pandemic, all sanitizers and disinfectants have become high in demand and continuously becoming one of the crucial items to kill pathogenic microbes. In addition, the robust adaptation of microorganism towards common antibiotics and general AgNPs has set an alarm for researchers to develop another promising antibacterial agent, especially with natural components from biomass. The biogenic synthesis of AgNPs from agricultural waste, which uses a safe and non-toxic process, has shown a promising strong antibacterial agent with broad spectrum coverage (Wolny-Koładka et al., 2022).

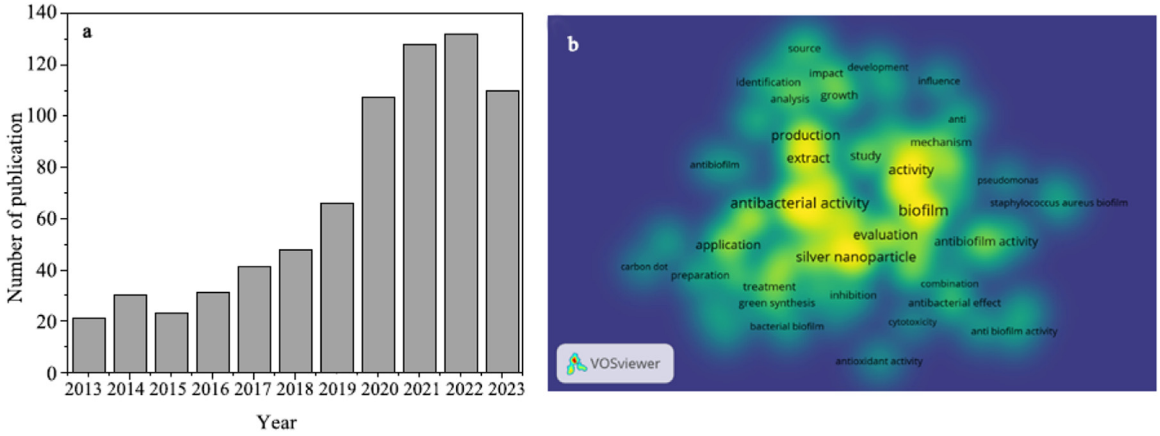


Fig. 1. Trend of data publication in Scopus 2013−2023 (a); VOSviewer visualization of research paper on keyword "biomass as antibacterial agent" according to Scopus database in 2013−2023 (b).

The beneficial effect of antibacterial properties from biomass has expanded its usage in mouthwash. Dental problems which include caries and plaque biofilm are formed by a complex microbial community that grows rigorously relying on the source of remaining foods on the teeth as their nutrient. Hence, an efficient antibacterial agent to be incorporated into mouthwash would help mitigate these problems. The replacement of chemical ingredients (alcohol, triclosan, chlorhexidine gluconate, etc.) with biomass-based ingredients for antibacterial properties provides a better solution for safer mouthwash consumption. Vikneshan et al. (2020) have synthesized biogenic selenium nanoparticles conjugate with increased surface area for better interactions with the bacterial community and excellent biocompatibility. Activated carbon isolated from jute sticks was reported to enhance the efficacy of selenium nanoparticles as antimicrobial agents (Devi et al., 2019). Kaur et al. (2020) studied the ability to combat bacteria of nanocomposites made from lignin-derived zinc oxide at different concentrations on both *E. coli* and *Bacillus megaterium* bacteria as each is Gram-negative and Gram-positive, respectively. The results showed that the developed lignin nanocomposite can be used as a future antimicrobial agent with great sun protection factor (SPF) value.

3. Biomass derivatives

3.1. Lignin

Lignin, which makes up 15 to 35 % of the lignocellulosic biomass generated by the wood and paper industries, is the world's second-most plentiful natural resource. It is composed of cross-linked polyphenolic structures, which are important for cell wall growth and support plants' structural integrity. Fig. 2 shows three main backbones: p-coumaryl alcohol (H) (1), coniferyl alcohol (G) (2), and sinapyl alcohol (S) 3. Mun et al. (2021) identified possible side chains in lignin structure from hardwood, i.e. compound 6−15 in Fig. 2 based on nuclear magnetic resonance spectroscopy result. Currently, merely 2 to 5 % of industrial lignin waste is being utilized profitably (Ridho et al., 2022). Most lignins are employed as lignosulfonates, which are mixed with construction materials for usage as superplasticizers in concrete (Breilly et al., 2021). The remaining is mainly disposed of discarded trash or used as inferior fuel (Cao et al., 2018; Sugiarto et al., 2022). The biopolymer lignin is drawing more and more consideration from scientists because of its potential usage in physical applications. Among other advantageous qualities, this polymer is plentiful, renewable, and makes up 30 % of all non-fossil organic carbon in nature (Bajwa et al., 2019). With a market value of 954.5 million Yuan (US dollar) in 2019 and an expected yearly increase of 2 % by 2027, lignin is currently manufactured in substantial quantities (Grand View Research, 2022).

Most of the lignin manufactured today is utilized as a boiler while just a tiny percentage is being used for value-added products like chemicals and energy sources. The physicochemical characteristics of lignin are influenced by the plant materials used, the isolation methods used, as well as the pulping process for treatment (Sahoo et al., 2011). Lignin is reasonably affordable and offers a lot of great qualities including a high amount of carbon, good thermal stability, antioxidant activity, and desirable stiffness (Ridho et al., 2022; Ariyanta et al., 2023a; Ariyanta et al., 2023b). However, significant differences in functional groups, chemical composition, and molecular weight can be observed among many lignin forms. These advantages encourage researchers to create lignin-based compounds with value-added properties for usage in many applications (Kai et al., 2016). Sugiarto et al. (2022) described cutting-edge techniques for modifying lignin and emphasized the lignin's special advantages for biomedical products, including its antioxidant, antibacterial, anti-UV, and biocompatibility properties (Fig. 3). Additionally, they provide a thorough analysis of the prospective uses of lignin in several biomedical disciplines, particularly in tissue engineering, bioimaging/biosensors, tumor therapy, and 3D printing (Sugiarto et al., 2022).

Natural biopolymer lignin is a potential option for secure and non-toxic green products (Ndaba et al., 2020; Sugiarto et al., 2022). Additionally, lignin's antibacterial ability has been the focus of in-depth investigation for many years (Nada et al., 2004). Some work reported that the phenolic fragment, which has a methyl group and C=C position, is responsible for the compound's antibacterial

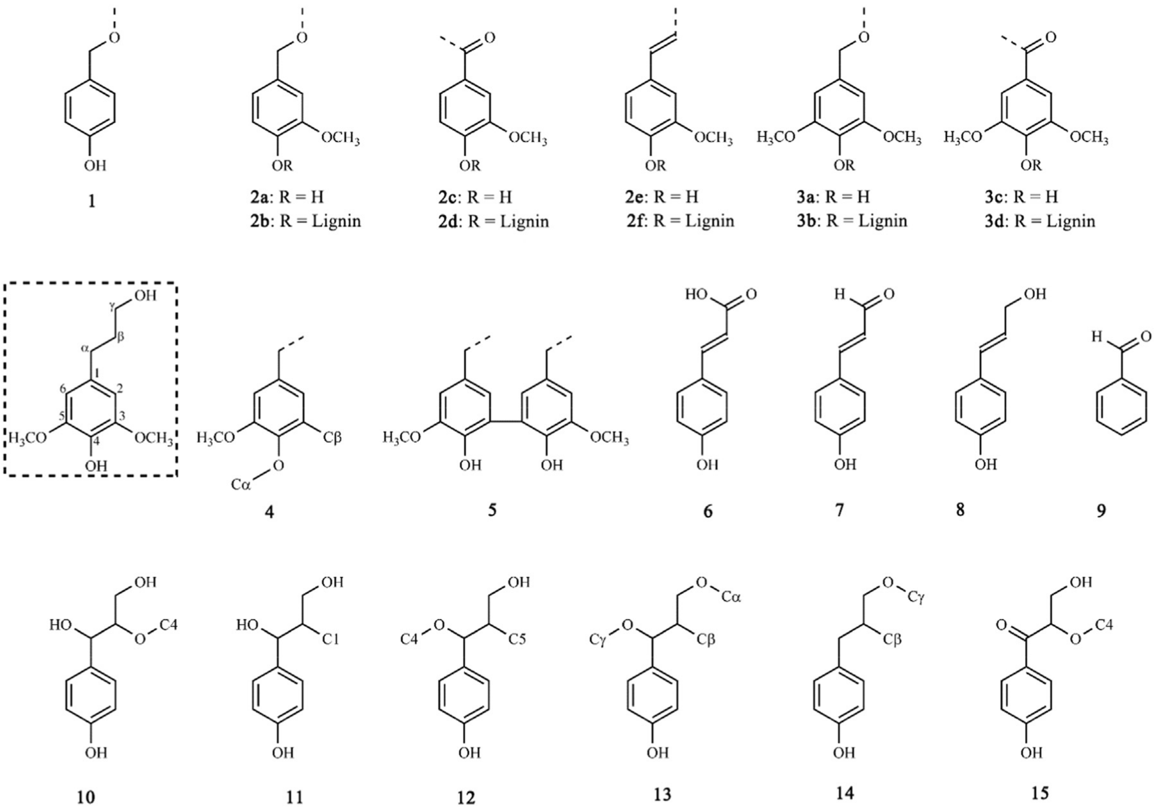


Fig. 2. Substructure of lignin (1−5) and its side chain (6−15) by ^{13}C nuclear magnetic resonance (Mun et al., 2021).

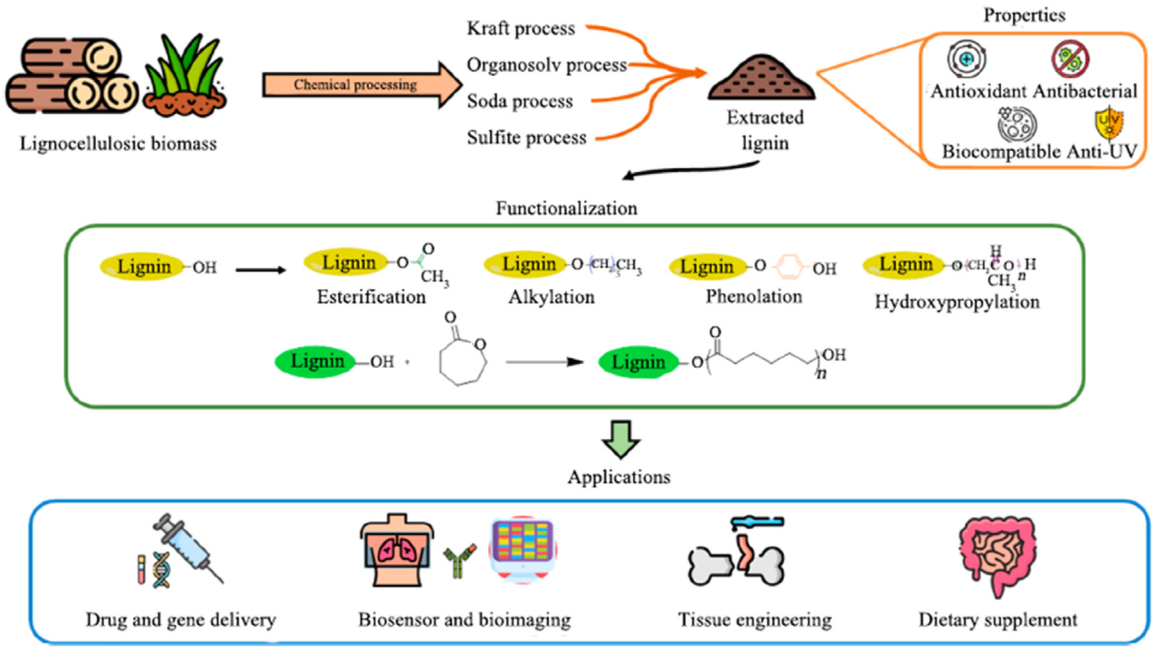
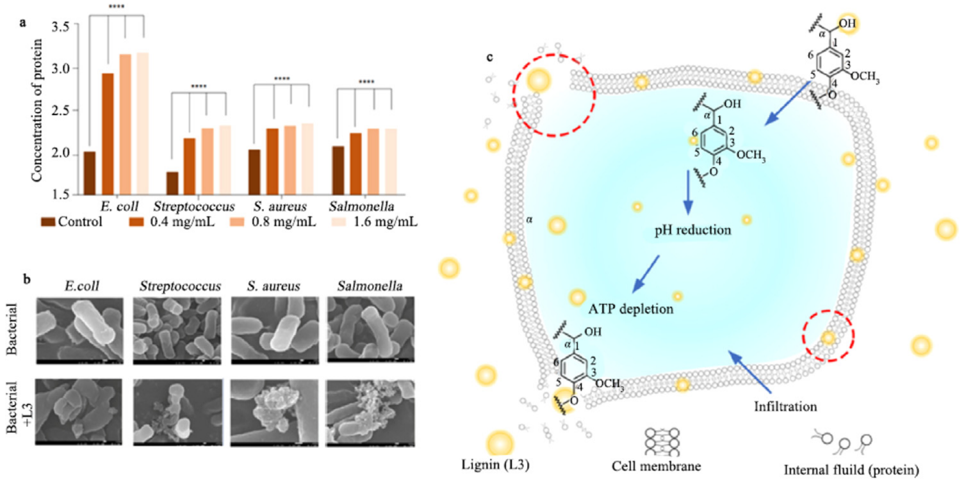


Fig. 3. A summary of lignin as a biomaterial (Sugiarto et al., 2022).



E. coli, *Escherichia coli*; *S. aureus*, *Staphylococcus aureus*; ATP, adenosine triphosphate.

Fig. 4. (a) Concentration of protein in bacteria culture solution treated by L3 lignin; (b) before-and-after morphological comparison of the bacterial cell wall treated with L3 lignin; (c) the suggested L3 antibacterial mechanism (C) (${}^{****}p < 0.000\ 1$) (Yun et al., 2021).

action (Nada et al., 2004; Kai et al., 2016; Ndaba et al., 2020). de Sousa Nascimento et al. (2001) found that organosolv lignin produced from banana peels had anti-inflammatory and antibacterial against *E. coli* bacteria. With the largest inhibitory zone against *E. coli* (Fig. 4a), Yun et al. investigation showed that fractionated organosolv lignin may have potent antibacterial effects against *E. coli, Streptococcus, S. aureus*, and *Salmonella. E. coli* had an excellent level of pathogenic disruption in Fig. 4b, which provides evidence of bacterial cell destruction. They discovered that fractionated lignin provides a lower molecular weight, a higher concentration of phenolic hydroxyl groups, and better antioxidant properties. It also showed that the created biopolymer destroyed the cell walls of Gram-positive and Gram-negative bacteria along with hindering the proliferation of pathogens. Overall, it was found that the substance with the lowest molecular weight and the highest phenolic content had the best antibacterial properties (Fig. 4c) (Li et al., 2022; Yun et al., 2021).

However, Gerbin et al. (2021) created films using colloidal nanoparticles or phenol-enriched oligomers with cellulose and lignin, where the latter reacted more favorably with the former to create a smooth-surfaced film. Additionally, the antimicrobial activity of both materials was examined, and antibacterial qualities were shown in the films against Gram-negative bacteria regardless of the lignin structure.

Fractionated organosolv lignin was reported to have potent antimicrobial properties. Using eco-friendly and green methods, lignin nanoparticles with the sizes of 75 and 215 nm have been successfully developed by Freitas et al. (2020). The lignin particles were stable at high temperatures and had a clearly defined chemical structure. Although research on a Caco-2 cell line proved the chemical, in this case, was not toxic, they showed antibacterial action against the diseases *Salmonella enterica* and *E. coli* (Freitas et al., 2020). An amorphous thermally stable film with antibacterial and biodegradable properties was made by combining lignin with polylactic acid. The extra lignin's capacity for preventing lipid oxidation and Gram-positive bacteria growth suggests that it may be employed in the food packaging industry (Chaubey et al., 2020). Lignin particles protected 5,10,15,20-tetrakis(4-hydroxyphenyl)-21H,23H-porphyrin (THPP) from losing its properties, such as the fluorescence and oxygen generation, as a drug carrier with good storage durability across a wide pH range. Only Gram-positive pathogens displayed flocculation after the bacterial wall breakdown when the drug was tested for Gram-positive and negative bacteria (Maldonado-Carmona et al., 2020). The reduction/inhibition rates for bacteria are presented in Table 1 (Štumpf et al., 2020). Hidayat et al. (2023) statistically proved the effect of family biomass, type of solvent, and bacteria types on lignin antibacterial properties. In general, molecular weight and the total amount of phenolics contribute to lignin's antimicrobial properties. The cell walls of Gram-positive and Gram-negative bacteria are more easily destroyed by a form of lignin nanoparticles (fractionated lignin) that have the largest amount of phenolics. The attention to using lignin as an antibacterial additive is lignin types, extraction method, particle size, solvent to dissolve lignin, and type of bacteria. Therefore, the appropriate application of lignin can be considered. Current applications of lignin as an antibacterial additive will be discussed in the next chapter.

3.2. *Tannin*

Tannins are secondary plant metabolites that belong to the polyphenol class and are found in several plant tissues as well as in a variety of meals and feeds. They are commonly referred to as phenolic compounds which are soluble in water with molar masses ranging from 500 to 3 000 g/mol. Tannins can be removed from biomass by using hot water, base, or organic solution (Huang et al., 2018; Cheng, 2021).

The two main categories of tannins found in terrestrial plants are hydrolyzable tannins and proanthocyanidins (condensed tannins). Hydrolyzable tannins can be hydrolyzed into smaller tannins, as implied by their name. Meanwhile, hydrolyzable tannins can be

Table 1

Summary of lignin potency as an antibacterial agent.

Lignin type	Extraction method	Particle size/shape	Material structure	Bacteria	Inhibition rate (%)	Reference
Lignin	Kraft lignin fractionated by dissolving in dimethylformamide and precipitated with methanol	-	Hydrogel	*S. aureus E. coli*	95.70 94.80	Xu et al., 2021
Lysine-modified enzymatic hydrolysis lignin	Enzymatic hydrolysis lignin, extracted from corn cobs	-	Emulsion	*S. aureus E. coli*	93.00 50.00	Chen et al., 2021
Fractionated lignin	Kraft pulping with the use of five-year-old moso bamboo	-	Particles	*E. coli Salmonella Streptococcus S. aureus*	95.61 89.60 66.62 64.68	Yun et al., 2021
Acylated lignin with porphyrin	Kraft lignin	200 nm (spherical)	Nanoparticles	*S. aureus, S. epidermidis*, and *E. faecalis*	99.90	Maldonado-Carmona et al., 2020
Lignin decorated with silver	Alkali lignin	-	Particles	*S. aureus E. coli*	99.99 99.90	Wang et al., 2021
poly(L-lactide) with lignin and $ZnFe_2O_4$	Alkali lignin	-	Particles	*S. aureus E. coli*	60.00 35.00	Lizundia et al., 2020
poly(L-lactide) with lignin and Ag_2O				*S. aureus E. coli*	60.00 5.00	
poly(L-lactide) with lignin and Fe_2O_3				*S. aureus*	40.00	
poly(L-lactide) with lignin and WO_3				*E. coli*	5.00	

Notes: S. aureus, Staphylococcus aureus; E. coli, Escherichia coli; S. epidermidis, Staphylococcus epidermidis; E. faecalis, Enterococcus faecalis.

broken down into more manageable substances like gallic and ellagic acid (Khanbabaee and van Ree, 2001). Condensed tannins and hydrolyzed tannins are two different forms of tannins. Plants contain both forms of tannins, but condensed tannins are more prevalent. Typical plant components where tannins can be found include leaves, fruit, bark, and stems. Tannins are abundant in acacia plants, pine bark, quebracho wood, gambier stems, and gambier leaves (Kumar Das et al., 2019).

Tannins have a well-known ability to interact with different metal ions to form chelates. Recent research has demonstrated that tannins also offer several health-enhancing qualities, such as antimicrobial capabilities, anti-inflammatory, antiviral, antibacterial, anti-toxin, and anti-carcinogenic activities (Chung et al., 1998; Huang et al., 2018).

Similar to lignin, tannin's antibacterial potency is demonstrated by its capacity to penetrate through the wall of a bacterial cell up to the interior membrane, disrupting the cell's metabolism and then cell crushing. Tannic acid's antimicrobial properties have been demonstrated against both Gram-positive and Gram-negative bacteria. Because Gram-negative bacteria have posed a significant barrier to modern medicine, the observed tannic acid action against them has been of particular importance. However, tannin activity is higher in Gram-positive bacteria than in Gram-negative bacteria (Kaczmarek, 2020). The mechanism is illustrated in Fig. 5. Polyphenols exert antibacterial action at three different levels: bacteria level, toxin level, and target cell level. At the bacteria level, polyphenols damage the membrane of the bacteria's structure, inhibit energy metabolism, toxin generation or secretion, and enhance target cell resistance (at the level of the target cell). Polyphenols can potentially react immediately with the produced toxins, altering their structure and action. Furthermore, it can operate at the level of target cells, improving their ability to resist toxins (Olchowik-Grabarek et al., 2020).

The antibacterial activity of tannin is influenced by elements such as concentration, type of bacteria, solvent/matrix type, temperature, pH, and action time (Obiang-Obounou and Ryu, 2013; Hidayat et al., 2023). The updates of tannin's antibacterial properties are shown in Table 2. Obiang-Obounou and Ryu (2013) explained that extrusion cooking at higher temperatures increased the antibacterial activity while the feed moisture was not notably different. The higher tannin concentrations, the higher the antibacterial activity (Vu et al., 2017; Roy Maulik et al., 2021). Meanwhile, the isolation method of tannin from biomass plays a critical role in antibacterial activity as stated by Rodrigues et al. (2014). Štumpf et al. (2020) explained growth medium strength had a significant effect on minimum inhibitory concentrations of different tannins isolated from mimosa, quebracho, chestnut, colorizer, and tannic acid against *E. coli*. In addition to the high tannin content of biomass, the microbial target is also important when selecting a tannin source for the antimicrobial application of a product. Unlike lignin which is not completely soluble in water and some inorganic solvents, the foremost consideration of tannin's antibacterial properties is biomass source, concentration, and extraction process. An inappropriate extraction process of tannin may not fully extract the phenolic content and lead to a lower concentration of tannin.

3.3. Cellulose

Cellulose, a type of polysaccharide, is the major compound found in biomass which consists of D-glucose as a main unit. Cellulose's antibacterial properties can only be emphasized in its derivatives such as after chemical modification (Coma et al., 2015). Bioactive chemicals must be immobilized or integrated into cellulose as a polymer matrix to perform specialized functions. Some

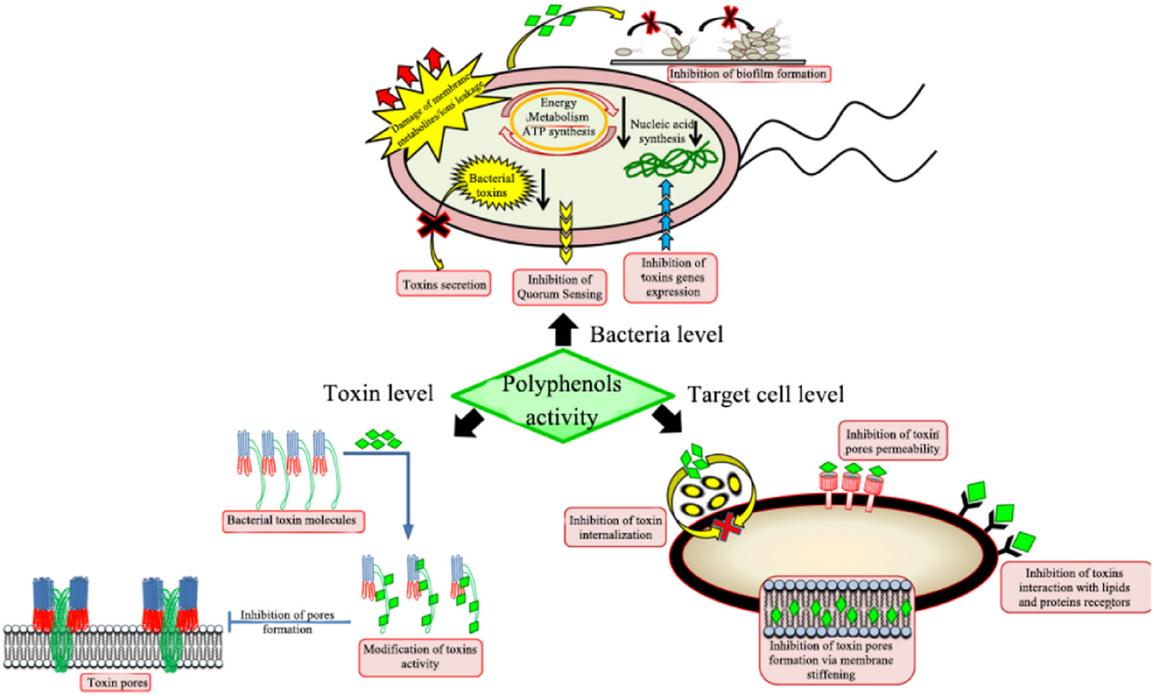


Fig. 5. The process of polyphenols' antibacterial activity at three different levels (Olchowik-Grabarek et al., 2020).

Table 2
A recent update of tannin as an antibacterial agent since the last decade.

Biomass source	Bacteria	Optimized parameter	Reference
Chestnut	*P. aeruginosa, B. subtilis, S. epidermidis*	Feed moisture, temperature extraction, and tannin concentration Summary: the increasing temperature did not influence the inhibition zone and vice versa for increasing moisture and tannin concentration.	Obiang-Obounou and Ryu, 2013
Dioscorea cirrhosa	*S. aureus, E. coli*	-	Yang et al., 2018
Eucalyptus Bark	*S. aureus, E. coli*	A tannin concentration of 200 g/L reduced bacterial growth by more than 90 %.	Roy Maulik et al., 2021
Psidium guineense (myrtaceae)	*P. aeruginosa, S. aureus*	Isolation method: The full extraction method created a higher inhibition zone than the partial (hydrophilic phase only) extraction method.	Rodrigues et al., 2014
Sapium baccatum	*R. solanacearum*	Tannin reduced the bacterial growth to 63 % and 83 % when its concentrations were 1 000 and 2 000 μg/mL, respectively.	Vu et al., 2017
Entada phaseoloides	*S. aureus*	Wound healing time: as the time increases (up to 21 days), the wound healing rate reaches 100 %.	Su et al., 2017
Chestnut, quebracho, mimosa, Colistizer, and tannic acid	*E. coli*	Growth medium strength: the concentration of the growing medium increased in all samples, and MIC values increased linearly.	Štumpf et al., 2020
Acacia mangium and *Acacia crasicarpa*	*P. acnes, S. aureus, B. subtilis, S. epidermidis*	Solvent and type of biomass significantly influenced the inhibition zone while bacteria types were not. The highest inhibition zone on tannin dissolved in ethanol (~1 cm).	Hidayat et al., 2023

Notes: P. Aeruginosa, Pseudomonas aeruginosa; B. Subtilis, Bacillus subtilis; R. Solanacearum, Ralstonia solanacearum; P. acnes, Propionibacterium acnes.

parameters in the chemical modification of cellulose to create antibacterial properties should be considered, such as ratio between matrix and bioactive compound, type of bioactive compound, and type of bacteria (Nemeş et al., 2022). Because cellulose does not have antibacterial activity, the antibacterial mechanism is defined by its bioactive compound. However, in general, the mechanism of cellulose-based antibacterial agents is divided into three steps: damaging bacteria cell membranes, inferring bacteria protein activity or deoxyribonucleic acid (DNA) synthesis, and generating reactive oxygen species (ROS) to damage bacteria cells (Bao et al., 2022).

The advantages of cellulose-based antibacterial agents are highly modifiable, hydrophobic, excellent biodegradability, low cost, good mechanical properties, and good biocompatibility (Bao et al., 2022). Recent updates of cellulose derivatives as antibacterial

Table 3
Recent updates for functionalization of cellulose-based antibacterial agent.

Bioactive compounds for functionalization	Bacteria type	Optimization parameter	Reference
Quaternary ammonium salts: dodecyl-trimethyl-ammonium bromide (DDTMABr), tetradecyl-trimethylammonium bromide (TDTMABr) and hexadecyl-trimethyl ammonium chloride (HDTMACl) Phosphonium salts: tri n-butyl-hexadecyl phosphonium bromide (HDTBPBr) and dodecyl-triphenyl phosphonium bromide (DDTPPBr) Extractants containing sulfur: thiourea (THIO) and 2-mercaptobenzothiazole (MBT)	*S. aureus* (ATCC 25923), *E. coli* (ATCC 25922), *C. albicans* (ATCC 10231), *P. aeruginosa* (ATCC 27853)	The ratio of extractant to cellulose was 0.012–0.5. TDTMABr had the best inhibition zone in the lowest ratio.	Nemeş et al., 2022
Metals nanoparticle: silver (Ag) and zinc oxide (ZnO) nanoparticles	*E. coli; S. epidermidis* (ATCC 49461)	Metal concentration (1 %–3 %) where increasing the metal narrowed the inhibition zone.	Pal et al., 2017; Onyszko et al., 2022
3-aminopropyl triethoxysilane (APTES)	*E. coli* (ATCC 11229); *S. aureus* (ATCC 6538)	The best solvent was ethanol and the ratio of tannin to APTES was 1:1.	Tummino et al., 2023

Note: C. albicans, Candida albicans.

properties are listed in Table 3. Nemeş et al. (2022) incorporated cellulose with some bioactive compounds, such as a group of quaternary ammonium salts, phosphonium salts, and extractants containing sulfur, the mass ratio of bioactive compounds to cellulose was 0.012–0.5. The shortest alkyl substituent chain had the highest antibacterial activity with 0.012 as the lowest ratio and 100 % inhibition rate against *Candida albicans* (*C. albicans*), *E. coli*, and *S. aureus*. Dissimilar to polyphenol structure in biomass, cellulose skeletons exhibit no antibacterial properties, and hence structural modification is a critical point. Antibacterial characteristics of cellulose derivatives are dependent on the bioactive compounds during the functionalization. In general, the ratio between bioactive compounds and cellulose is a main issue.

3.4. Hemicellulose

Hemicelluloses as the second-most prevalent macromolecule in the world, are found in the walls of vegetal cells for 15 % to 35 % of the plant's total weight (Lobo et al., 2021). Different from cellulose, hemicelluloses are polymers formed by combining distinct sugar units that are organized in varying proportions and have different/multiple substituents. As a lignocellulosic polymer, hemicellulose is bound to lignin via covalent bonds (α-benzyl ether linkages) and bonded to cellulose via hydrogen bonds. Hexoses (-D-galactose, -D-mannose, and -D-glucose) and pentoses (-L-arabinose and -D-xylose) make up a majority of the monosaccharide units that make up hemicellulose, while other sugars (fructose and rhamnose) make up a low percentage. Additionally, uronic acids are found, including D-glucuronic acid, D-galacturonic acid, 4-O-methyl-D-glucuronic acid, and acetyl groups (Fernandes et al., 2013; Zhou et al., 2016). The hemicellulose structure is presented in Fig. 6 below.

Hemicelluloses have an extensive amount of hydroxyl groups in their side chains and backbone. It is capable of being chemically changed to various functional groups by reactions like esterification, etherification, graft copolymerization, and others to address a variety of applications as a biopolymer. Many commercial biopolymers and value-added products resulted from hemicellulose have wide applications such as from the environment to healthcare as an antibacterial substance (Ahmad et al., 2020; Lobo et al., 2021). Hemicellulose-based polymers offer antimicrobial potential although not much research has been done compared to tannin and lignin. Nonetheless, due to their components, these polymers have a high antibacterial potential. Ahmad et al. (2020) created a hemicellulose-based film as an antibacterial agent for wound dressing because current natural-based biofilm from chitosan, cellulose, and lignin had lack of stability, exudate-absorbing capability, mechanical strength, and adhesion. Hemicellulose can be used as an antibacterial agent before or after functionalization where the activity depends on biomass types, concentration of hemicellulose, and the bacteria types (Bouaziz et al., 2017; Ragab et al., 2018). Table 4 reported some research on the bacterial activity of hemicellulose-based polymer toward the type of bacteria. Although hemicellulose acts as an antibacterial agent, the functionalization of hemicellulose should be considered to increase the efficiency of combating bacterial growth. Besides, the concentration of hemicellulose was also reported as the main parameter for bacterial reduction. Many researchers combined hemicellulose with metal substances to increase the antibacterial efficacy yet wholly bio-based hemicellulose derivatives still need to be explored such as the functionalization of hemicellulose with chitosan or any cationic copolymer derived from nature.

Hemicellulose's antibacterial action depends on chemical changes made by the added functional groups, the kinds of connections created, the patterns of substitution created, and the degree of substitution attained (Salam et al., 2011). Xylan has been widely researched as a hemicellulose with antibacterial activity. According to research by Fu et al. (2020), gels containing xylan, gelatin glycerol, and nicotinamide were effective at killing yeast but less effective at killing *Bacillus subtilis* (*B. subtilis*) and *S. aureus*.

Further explanation will explain the type of functionalized hemicellulose, chemically altered to provide molecules with unique characteristics for antimicrobial applications.

a. Esterification

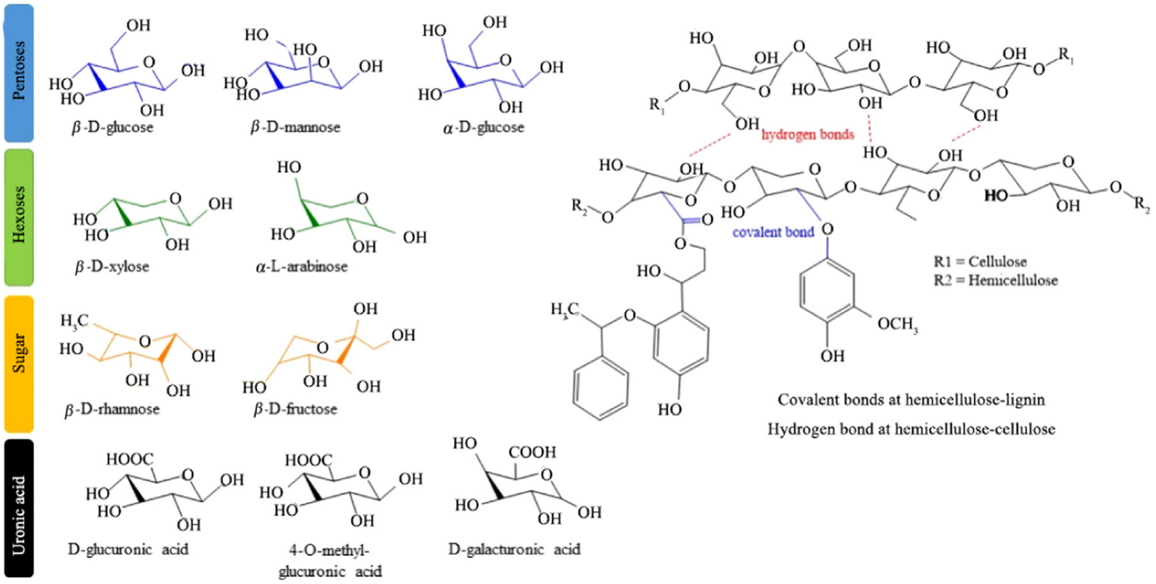


Fig. 6. Monosaccharides units in hemicellulose structure and their linkages.

Esters are made by the interaction between carboxylic acid groups and alcohols (or carboxylic acid derivatives such as acid chlorides and acid anhydrides). Hydrogels, paper coatings, medical implants, and biodegradable films based on hemicellulose have all been described (Fundador et al., 2012; Zamora Zamora et al., 2022). Nechita et al. (2023) showed that xylan-coated paper exhibited mild antifungal efficacy against common fungi and barely a little antibacterial impact on *S. aureus.* Chitosan biopolymer can be used to increase the swelling and solubility of films, as well as the capacity of xylan hemicelluloses to create films. The complexes of polyelectrolyte in the xylan-chitosan films maintained their integrity in a swelled condition. Acetylated cellulose, starch valerate, starch butyrate, starch propionate, acetylated starch, acetylated xylan, and starch hexanoate are examples of esterified polysaccharides that can be utilized to slow down anaerobic biodegradation of bioplastics.

Acetylation of xylan is often the major polymer component using acetic anhydride. In general, acetylation of polysaccharides increases polymer chain mobility because acetyl groups hinder the development of strong hydrogen bonds and tight packing of polymer chains. This is confirmed by X-ray diffraction, which also exposes the amorphous structure of the acetylated xylan (Nechita et al., 2023).

A specific kind of esterification reaction that results in oleoyl esters is oleoylation. In paper-based food packaging, they demonstrated distinct hydrophobic and high moisture barrier qualities as well as antibacterial activity. In addition, the esterification reaction can be carried out by replacing the hydroxy group via lauroylation, fluorination, and crosslinking/graft copolymerization but it does not have many applications in the health sector, especially as an antimicrobial.

b. Etherification

Most commonly, the formation of ethers from polysaccharides is utilized to control solubility, give stability against microorganisms (biodegradability), or provide film-forming properties. Alcohol and an alkylating agent can react with one another to form ether when a base is present. Sulfonates, alkyl halides (bromides, chlorides, and iodides), and epoxides are common alkylating substances. Kapil et al. (2022) modified hemicellulose by using benzyl chloride to get carboxymethylated xylan (CMX) and transform it into biofilm. The antibacterial showed that CMX biofilm had the greatest antibacterial activity against *B. subtilis* and *Pseudomonas*, with the inhibition diameter of 33.5 and 30.5 mm, respectively. Queirós et al. (2017) combined CMX with other active compounds to boost the antibacterial properties of biofilm, such as linoleic acid, ammonium zirconium carbonate, and agar. The CMX: agar: linoleic acid film had the best ability against *Bacillus cereus* (*B. cereus*) and *S. aureus*.

3.5. Chitosan/chitin

N-acetylglucosamine monomer units, sometimes referred to 2-acetamido-2-deoxy-D-glucose, are the components that make up blocks of the polysaccharide described as chitin. It contains nitrogen of more than 7 % and has acetylation levels of less than 40 %. As the primary structural element of the exoskeletons of arthropods, mollusk shells, and the cell walls of fungi and yeasts, chitin appears as a white, rigid, inelastic, and nitrogenous substance that is widely present in nature (Guarnieri et al., 2022). Although chitin was discovered before cellulose, the economics of its manufacturing prevented its industrial application and that of its derivative, chitosan. Chitosan, the world’s second most abundantly available cationic polysaccharide can be created when the acetyl groups from chitin are removed. It is produced from green algae, fungi cell walls, crustacean exoskeletons, insects, and arachnid cuticles (Marinho et al.,

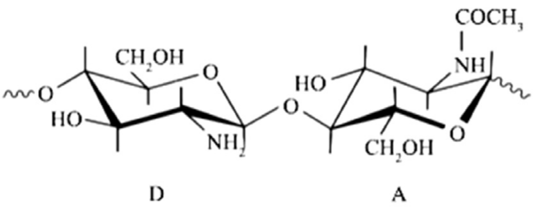
Table 4
Bacteria reduction or inhibition rates of hemicellulose-based materials.

Hemicellulose type	Biomass source	Bacteria	Bacteria reduction/inhibition (%)	Reference
Non-functionalization	Almond gum	*Actinomycetes, S. typhimurium, K. pneumonia, L. monocytogenes, S. aureus, S. enterica, P. aeruginosa, B. thuringiensis*, and *B. subtilis*	Increased at increasing concentration of hemicellulose; a strong the antibacterial effect at 40 mg/mL against *B. thuringiensis, S. enterica,* and *P. aeruginosa.* Moderate effect against *Actinomycetes, S. typhimurium, K. pneumonia, L. monocytogenes*, and *B. subtilis.*	Bouaziz et al., 2017
Phosphorylated hemicelluloses	Palm frond and rice straw	*S. aureus, E. coli*, and *C. albicans*	The inhibition diameters were 22, 22, and 26 mm, respectively.	Ragab et al., 2018
Xylan functionalized with trimethoxysilylpropyl methacrylate (TMSPMA) and poly(N-vinylcaprolactam)	Agave bagasse	*S. aureus, E. coli,* and *P. aeruginosa*	Exhibit a releasing efficacy for 3 days at 37°C.	Arellano-Sandoval et al., 2020
Xylan-based antimicrobial	Paper products (sugarcane bagasse	*E. coli*	-	Xu et al., 2020
Xylan–chitooligomer–zinc complex (XCGZC)	Corn cobs	*B. subtilis, S. typhimurium*, and *B. megaterium*	Increasing with the increase of XCGZC concentration when the diameter is 13–35 mm.	Wu et al., 2013
Arabinoxylan film	psyllium husk (film composite)	*E. coli and S. aureus*	No antibacterial activity	Ahmad et al., 2020
		E. coli and *P. aeruginosa* (Gram-negative bacteria)		Ahmad et al., 2020
		S. aureus (Gram-positive bacteria),	Significant activity	

Notes: S. typhimurium, Salmonella typhimurium; K. pneumonia, Klebsiella pneumonia; L. monocytogenes, Listeria monocytogenes; S. enterica, Salmonella enterica; B. thuringiensis, Bacillus thuringiensis; B. megaterium, Bacillus megaterium.

Table 5
Sources of chitin/chitosan.

Source	Name
Sea animals	Crustaceans, annelids, coelenterates, lobsters, mollusks, prawns, shrimps, krill, and crabs
Insects	Scorpions, cockroaches, brachiopods, beetles, spiders, and ants
Microbes	Green and brown seaweed, yeast, mycelia penicillium, fungi, chytridiaceae, blastocladiaceae, ascomycetes, and spores



D, glucosamine unit; A, N-acetylglucosamine unit.

Fig. 7. Structure of chitin and chitosan (de Queiroz Antonino et al., 2017).

2022). Crab, shrimp, prawn, and lobster shells are the primary sources for manufacturing chitin (Table 5). Chitin (15 %–40 %), magnesium carbonate (20 %–50 %), protein (20 %–40 %), calcium, and other minor components (such as lipids and astaxanthin) make up the majority of crustacean shells (de Queiroz Antonino et al., 2017; Riofrio et al., 2021). Fig. 7 shows the structures of chitin and chitosan. The existence of the amine group that remains after the deacetylation process resulted in chemical and natural modification of chitosan. The solubility of chitosan is high in diluted solutions of numerous inorganic and organic acids at pH 6 because of its amino group protonation. Because chitosan is polycationic, it can interact with polyanions to form polyelectrolyte complexes. These characteristics make it possible to be found in various materials, including flakes, beads, membranes, and sponges. It may also be made into films, fibers, hydrogels, microparticles, and nanoparticles and has good film-forming ability. Additionally, chitosan has numerous hydroxyl (-OH) and amino ($-NH_2$) groups in its molecular structure, making it useful for both fire safety and

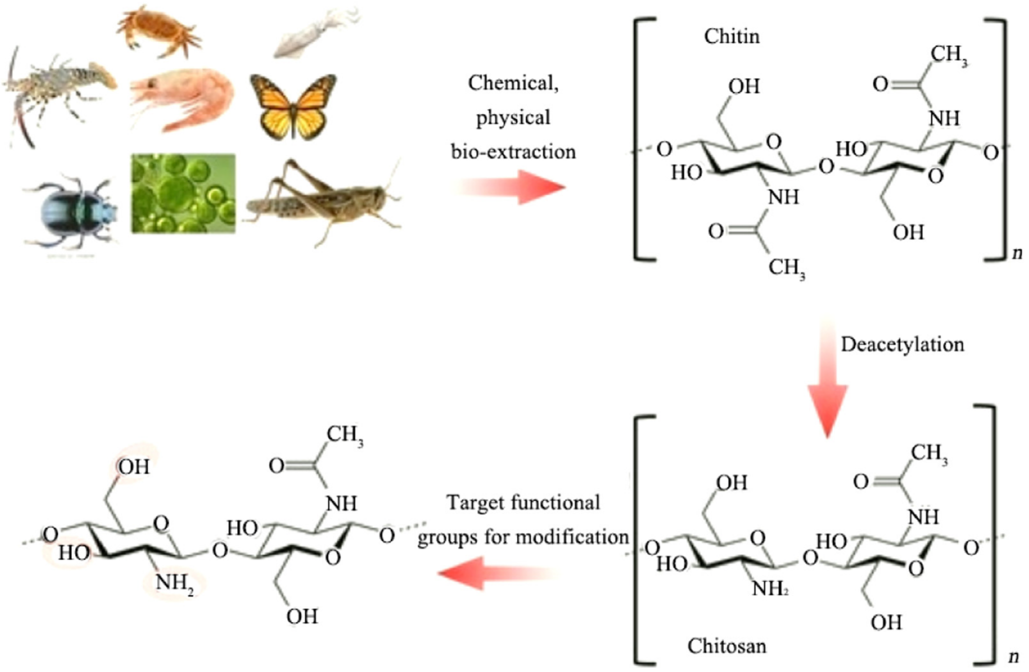


Fig. 8. Process of chitosan formation (Pellis et al., 2022).

water treatment (Tang et al., 2023). The US Food and Drug Administration has given it the Generally Regarded as Safe certification (Sebastian et al., 2019).

Commercial chitosan production involves strong alkali and crustacean chitin deacetylation (Fig. 8). From an industrial standpoint, this technique has significant drawbacks, including unpredictable product characteristics, the seasonal and restricted crustacean supply, and processing challenges, particularly with the vast amounts of concentrated alkaline solution wastes (Tayel et al., 2014).

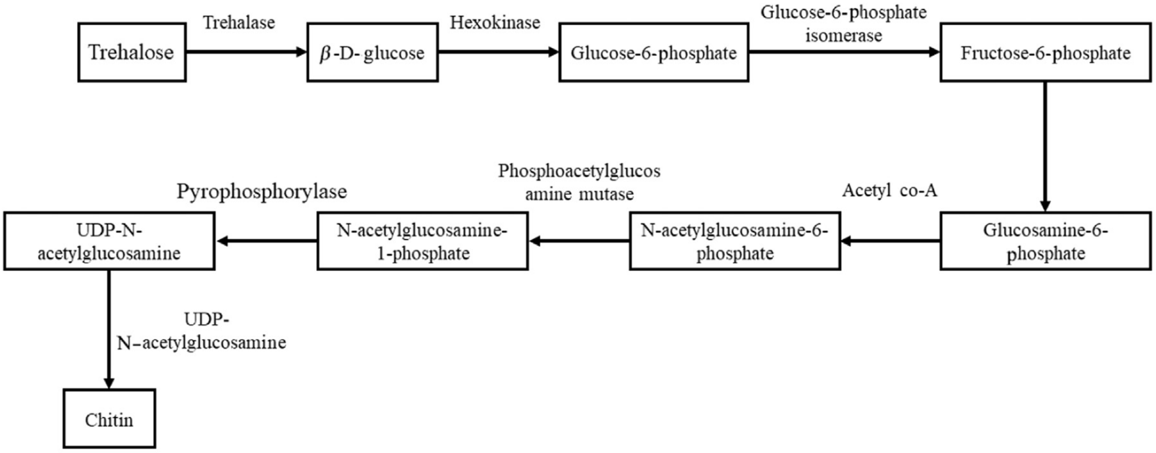
Since the claimed manufacturing processes mostly depend on the source's composition, which varies substantially from one species to another, they are quite inconsistent. Most of these techniques rely on chemical procedures such as from acids: HCl, HNO_3, H_2SO_4, and CH_3COOH to separate the protein from inorganic materials (Kaczmarek et al., 2019). On the other hand, a mild alkaline and acidic treatment is used to extract chitosan from a fungus. This method is regarded as environmentally friendly because it avoids the need for a demineralization phase. In addition, fungal chitosan possesses a medium-low molecular weight and good bioactivity while being free of allergenic prawn protein. The manufacture of chitosan from fungi is not, however, upsized to an industrial scale (Abdel-Gawad et al., 2017).

The synthesis route of chitin can be broadly divided into five different stages as follows (Pellis et al., 2022). The same is shown in Fig. 9.

a. The N-acetylglucosamine-6-phosphate synthesis from sugars, i.e., glucose, trehalose, or glycogen via the hexosamine process.
b. The amino sugar uridine diphosphate N-acetylglucosamine (UDP-N-acetylglucosamine) synthesis.
c. UDP-N-acetylglucosamine polymerization via chitin synthase into chitin.
d. Chitin formation along the cell membrane and dissipation into the extra-cellular space.
e. Chitin nanofibrils assembly.

At present, chitosan and its derivatives are used in various sectors, including medicine and biological medicine, pharmaceuticals, cosmetics, food processing and nutrition, hygiene and personal care, farming and agro-chemistry, edible film industry, textile and paper industries, and food packaging. Chitosan with a low molecular weight and nitrogen is appropriate for textiles, food, photography, medicinal, and ecological uses, whereas chitosan with a high crystallinity is good for constructing tissue engineering platforms due to its stiffness and higher mechanical properties. These applications come as a kind of formulations, suspensions, and particulates, i.e., resins, beads, nanoparticles and sponges, spheres, gels/hydrogels, and foams (Huq et al., 2022; Pellis et al., 2022). The characteristics, applications, and forms of chitosan are displayed in Table 6.

Chitosan also offers many benefits over chemical antimicrobials and disinfectants since it has a wider range of activity, a stronger antimicrobial effect, and a greater rate of microbial destruction without being hazardous. Chitosan possesses bactericidal and bacteriostatic properties. The most widely recognized process involves chitosan's polycationic properties, which enables it to engage negatively charged species of bacteria cell membranes. Furthermore, its chelating characteristics make it a good antifungal agent (Morin-Crini et al., 2019).



UDP-N-acetylglucosamine, amino sugar uridine diphosphate N-acetylglucosamine.

Fig. 9. Synthesis route of Chitin (adapted from Pellis et al. (2022)).

Table 6
Characteristics and applications of chitosan.

Characteristic	Application	Form
Biodegradable	Water purification	Beads
Biocompatible	Cosmetics	Resins
Non-toxic	Biomedical devices	Foams
Adhesion	Drug delivery	Nanoparticles
Adsorption	Antimicrobials	Sponges
Optical properties	Catalysts	Gels/hydrogels

Chitosan is more prone to interact with negatively charged components in bacterial membranes, i.e., nucleic acids, proteins, and anionic polysaccharides that is crucial for antibacterial activities. Chitosan-based hydrogels can help medical condition by creating a favorable environment for healing, lowering wound inflammation, and controlling infection because of their anti-inflammatory and antibacterial characteristics. Furthermore, when loaded with antimicrobial drugs, it can further suppress microorganisms, expediting wound healing (Liu et al., 2018a; Aranaz et al., 2021). The antibacterial performance of chitosan is influenced by several factors as shown in Fig. 10. The most generally accepted mechanisms of antibacterial actions of chitosan can be enumerated by the 4 models which include:

1. Chitosan molecules that are positively charged engage with the negatively charged compounds on the bacterial surface. Chitosan interacts with the bacteria's membrane to change cell permeability.
2. Interaction of products of hydrolysis dispersed with microbial DNA, resulting in messenger ribonucleic acid (mRNA) and protein synthesis inhibition.
3. Chitosan also prevents the growth of bacteria by chelating nutrients and critical metals.
4. Chitosan on the cell surface may produce a polymer barrier that prevents nutrients or functions as an oxygen shield that can stop the spread of aerobic microorganisms.
5. The mechanism of chitosan on Gram-positive bacteria, Gram-negative bacteria, and fungi is depicted in Fig. 11 (Yan et al., 2021).

Numerous studies have looked at how well chitosan and its derivatives fight bacteria. For instance, researchers created fungal chitosan from dates syrup, which was employed as a natural preservative and antibacterial agent, to protect the microbiological and sensory quality of minced meat. Fungal chitosan was investigated and contrasted with potassium sorbate, a common commercial meat preservative, as a safe and natural preservative for minced meat. They also investigated fungal chitosan and potassium sorbate-treated meat activity against *S. aureus* and *E. coli* microbes. It was observed that fungal chitosan has significantly stronger antibacterial action than potassium sorbate (Tayel et al., 2014).

In addition, chitosan was modified to improve its antibacterial characteristics by conjugating N-halamines with hydrophobic alkyl chains to inhibit bacterial growth and diminish bacterial adhesion. This two-step process boosted the bactericidal abilities of chitosan films, specifically against *S. aureus*, and increased the hydrophobic nature while reducing bacterial adhesion. The findings imply that chitosan films treated with chlorinated hexanal can be employed as a powerful antibacterial filter layer for masks (Chen and Chien, 2022).

Biomass composites were fabricated from chitosan (CS), sodium phytate (PA-Na), and nano-cellulose (NC) with epoxy and were analyzed to determine their antimicrobial performance and water/fire safety. According to the findings, the epoxy composite containing 5 % (*w*) CS/NC/PA-Na had a higher limiting oxygen index value than the control epoxy, rising to 26.6 % from 24.5 %.

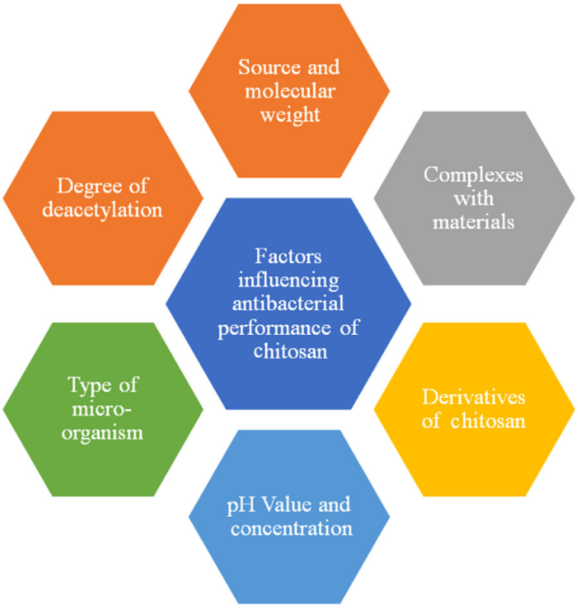


Fig. 10. Factors influencing the antibacterial characteristics of chitosan.

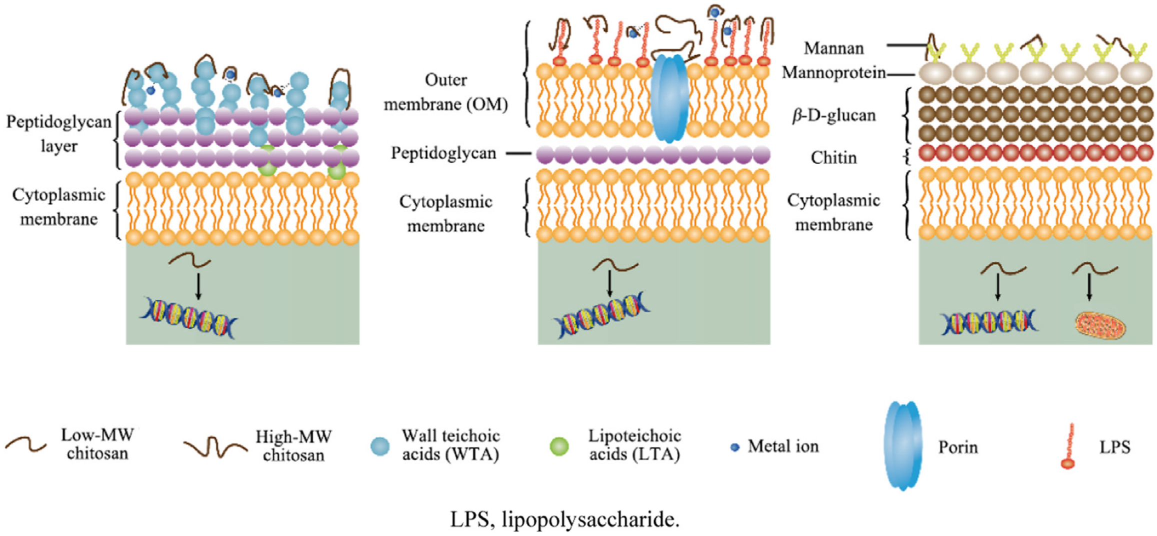


Fig. 11. Chitosan action modes on Gram-positive (A), Gram-negative (B), and fungi (C) (Yan et al., 2021).

Additionally, it was demonstrated that epoxy CS/NC/PA-Na prevented the growth of bacteriostasis rates colonies, particularly *E. coli*, proving the material's potential antibacterial qualities (Tang et al., 2023).

Zhu et al. examined the impact of dual-frequency (15 and 20 kHz) ultrasound on the physical, chemical, and antibacterial characteristics of chitosan produced from *Ganoderma lucidum* spore powders compared to single-frequency irradiation. The enhanced effect of utilizing superimposed ultrasonic beams from two variations of transducer orientations was indicated by the characteristics of the synthesized chitosan. According to findings, the synthesized chitosan helped L929 cells proliferate more effectively and showed better antibacterial properties against microbes such as *S. aureus* and *E. coli*. Furthermore, the two-transducer USAD-prepared chitosan showed better characteristics compared to the control group (Zhu et al., 2019).

Auricularia chitosan's antibacterial abilities were examined in research against *E. coli* and *S. aureus*. Using various NaOH concentrations and temperatures for hours, chitinous material from *Auricularia* was deacetylated and deproteinized. The results also demonstrated that both derived and commercial chitosan had antibacterial activity against *E. coli* and *S. aureus* that were concentration-dependent, meaning that as the level of concentration increased, so did the activity. Furthermore, it was shown that both chitosan showed considerably better inhibition on streptomycin sulfate against *S. aureus* and equivalent against *E. coli*. The fact that extracted chitosan inhibited both *E. coli* and *S. aureus* with bigger zones of inhibition than commercial chitosan suggests that extracted chitosan is superior to commercial chitosan in inhibiting both Gram-negative and Gram-positive bacteria. This might be a result of the high extracted chitosan's deacetylation degree (86.81 %) compared to the commercial one (83.66 %) (Chang et al., 2019).

Chitosan-based films were fabricated using a fungus extract taken from an edible species *Tricholoma terreum* by Koc et al. (2020). Chitosan films incorporated with fungal water extracts were predicted to enhance the material's antibacterial and antioxidant characteristics. *Streptococcus mutans, Enterobacter aerogenes, Bacillus thuringiensis, E. coli, S. aureus, Proteus vulgaris, Proteus mirabilis, Pseudomonas aeruginosa* (*P. aeruginosa*), and *Salmonella typhimurium* among the pathogens were utilized to analyze this. Native film of chitosan had lower antimicrobial efficacy than chitosan-fungal extract film which against practically all examined microorganisms, showing the best antibacterial abilities. The zone values of chitosan-fungal extract film increased by 22 % compared to the diameter of the chitosan-control film (Koc et al., 2020).

Chitosan and its derivatives are also gaining popularity as micro/nanoparticles or emulsions for antibacterial coating or bioactive food packaging. Fungal contamination is among the prevalent reasons for food degradation. Chitosan may impact fungal cells, leading to swelling and hyphae damage as well as molecular disarray and structural changes in the plasma and cytoplasm membrane. According to reports, incorporating chitosan into pasteurized palm sap might be used as an alternative strategy to increase its life. Using chitosan (0.50 g/L) for pasteurization and low-temperature storage, palm sap may be preserved for approximately 1.5 months (Huq et al., 2022).

The remarkable antibacterial properties of chitosan and water-soluble N,N,N-trimethyl chitosan chloride piqued researchers' interest in C-6 deoxy derivatives of chitosan. Jardine and Sayed (2018) created 6-deoxy-6-amino chitosan first using 6-halo and 6-azido intermediates. 6-deoxy-6-amino chitosan, which was first tested as a gene carrier and shown to have minimal cytotoxicity and optimum transfection effectiveness, is soluble under physiological conditions and at neutral pH.

When chitosan is applied as a surface coating, the polymer chain arrangement on the surface determines how effective it is against germs because the amine groups that are necessary for the antibacterial activity must be accessible for contact with bacteria. Vaz et al. (2018) investigated the possibility of functionalizing polytetrafluoroethylene (PTFE) substrates treated with plasma with chitosan using linker molecules. Their findings showed that the composition of the surface was appropriate to play as an antimicrobial surface because of the interaction of amine groups with the *Xylella fastidiosa* cell wall, leading to an improved reaction than glutaric anhydride (GA) and poly(ethylene–glycol) bis(carboxymethyl) ether (PEGb) samples. Alginate fiber can be coated with chitosan using a procedure developed by Dumont et al. (2018) that can be applied on an industrial scale. A chitosan acetate bath was used to coat the chitosan, which was then neutralized with 0.1 mol/L $Ca\ (OH)_2$ aqueous solution. The alginate/chitosan fibers maintain the absorbency and mechanical qualities of alginate while incorporating around 10 % (*V*) chitosan through an exterior coating. The alginate fibers with chitosan coating showed superior antibacterial action against *S. aureus* and *E. coli*. According to preliminary assessments, chitosan's primary mode of action on microorganisms would be through surface impacts. These findings are a true proof of concept for the use of chitosan-coated alginate fibers in textile and wound dressing applications to combine the antibacterial efficacy of chitosan with calcium alginate's wound-healing properties to combat nosocomial infections, in particular against healthcare-associated and antibiotic-resistant types (Dumont et al., 2018).

The antibacterial activity of chitosan nanoparticles (ChNP) against *K. pneumoniae, E. coli, S. aureus,* and *P. aeruginosa* was examined by determining the minimum inhibitory concentration (MIC) and comparing it to chitosan and chitin activity. Compared to chitosan and chitin, ChNP compounds demonstrated a higher antibacterial action against all microorganisms. With the use of the crystal violet test and congo red agar growth, the antibiofilm activity was investigated (Divya et al., 2017). The molecular weight and size of chitosan and its derivatives influence the majority of their physiological activities and functional characteristics. Finding new chitosan derivatives from low mammalian toxicity should be a focus of research and development to boost the feasibility. Besides, as a cationic polymer, the functionalization chitosan with amphiphilic substances from biomass such as lignin and tannin should be explored to enhance the antibacterial capability of chitosan.

The seaweed/marine macroalgae are non-flowering plants devoid of true stems, leaves, and roots and grow under different environmental conditions like high temperature, pressure, light, salinity, and desiccation. These natural species contain enormous and valuable bioactive compounds, with the main composition of chitosan, polyphenol, and alginate that possess pharmacological and biological properties like antibacterial, antifungal, antioxidant, scavenging, and antimalaria, respectively. Different researchers have utilized the seaweed species for studying the antibacterial properties (Table 7), e.g., the essential oil viz extraction from *Laminaria japonica* (LJEO) seaweed using microwave-hydrodistillation against three food-borne pathogens, which include *B. cereus, E. coli,* and *S. aureus* for antibacterial and antioxidant activity was performed by Patra et al. (2015) where they found that LJEO was effective against *B. cereus* and *S. aureus* species.

Boisvert et al. (2015) extracted three edible seaweeds from Saint Lawrence Estuary through a pressurized liquid extraction method and performed the antibacterial activity of the extracts from *Saccharina longicruris, Ascophyllum nodosum*, and *Ulva lactuca* against the food spoilage bacteria *E. coli, Micrococcus luteus, Brochothrix thermosphacta*. It was found that *U. lactuca* exhibited the highest growth inhibition with *E. coli* (69.5 %), and the growth inhibition with *M. luteus* and *B. thermosphacta* were 61.4 % and 21.4 %, respectively (Boisvert et al., 2015). Seenivasan et al. (2012) studied the antibacterial and phytochemical analysis of three species of seaweeds, which include *Codiumadhaerens anderson* (green algae), *Sargassum wightii* (brown algae), *Acanthophora spicifera* (red algae) against different human pathogenic bacteria obtained from intertidal region Mandapam coastal water. It was observed that the highest zone of inhibition in *Vibrio cholerea* (13 mm) (Seenivasan et al., 2012). Suresh et al. (2015) isolated a pigment *Halolactibacillus alkaliphilus* MSRD1 from seaweed using silica gel column chromatography, which displayed excellent inhibition against *S. aureus* (16 mm) and *Salmonella typhi* (14 mm). Rajeshkumar et al. (2021) studied copper oxide nanoparticles using seaweed (*Sargassum longifolium*) extract for antibacterial and antioxidant properties through agar well diffusion method with pathogenicity against Vibrio

Table 7
A recent update of seaweed as an antibacterial agent.

Bacteria	Bacteria reduction/inhibition (%)	Reference
B. cereus, E. coli, and *S. aureus*	*L. japonica* excellent result against *B. cereus* and *S. aureus*	Patra et al., 2015
E. coli, M. luteus, B. thermosphacta	*E. coli*, 69.5 %; *M. luteus*, 61.4 %; *B. thermosphacta*, 21.4 %	Boisvert et al., 2015
S. aureus, V. cholerae, Shigelladysentriae, Shigellabodii, S. paratyphi, P. aeuroginosa, and *K. pneumoniae*	*V. cholerae* (13 mm)	Seenivasan et al., 2012
S. aureus, and *S. typhi*	*S. aureus* (16 mm), *S. typhi* (14 mm)	Suresh et al., 2015
V. parahemolyticus, A. hydrophila, Serratia marcescens, and *Vibrio harvey*	*S. marcescens* (14 mm), *V. parahemolyticus* (16 mm), and *A. hydrophila* (17 mm)	Rajeshkumar et al., 2021
E. coli, K. pneumonia, S. typhi and *V. cholerae*	*A. subulate* (9.2 mm)	Radhika et al., 2012
B. subtilis, E. coli and *S. typhi*	excellent	Kumaresan et al., 2018
S. aureus, E. coli	good	Rajaboopathi and Thambidurai, 2018
S. aureus, E. coli, E. faecalis, P. aeruginosa	7−14 mm	Afrin et al., 2023

Notes: B. cereus, Bacillus cereus; L. japonica, Laminaria japonica; M. luteus, Micrococcus luteus; B. thermosphacta, Brochothrix thermosphacta; V. cholerae, Vibrio cholerae; S. paratyphi, Salmonella paratyphi; S. typhi, Salmonella typhi; P. aeuroginosa, Pseudomonas aeuroginosa; S. marcescens, Serratia marcescens; V. parahemolyticus, Vibrio parahemolyticus; A. hydrophila, Aeromonas hydrophila; A. subulate, Agardhiella subulate.

parahemolyticus, Aeromonas hydrophila, Serratia marcescens, and Vibrio harvey effectively. Radhika et al., (2012) selected five different types of seaweeds (*Sargassum wightii, Padina tetrastomatica, Caulerpa racemosa, Agardhiella subulata,* and *Stoechospermum marginatum*) and investigated their antibacterial activities against four pathogens (*E. coli, Klebsiella pneumonia, Salmonella typhi,* and *Vibrio cholerae*). They found the maximum zone of inhibition for *Agardhiella subulate, Stocheospermum marginatum* against *K. pneumonia, Caulerpa racemosa* against *Vibrio cholerae*, and *Sargassum wightii* showed no activity against *E. coli, K. pneumonia* species, respectively (Radhika et al., 2012).

Kumaresan et al. (2018) synthesized zirconia nanoparticles using brown algae *Sargassum wightii*. They studied its antibacterial property against Gram-positive and Gram-negative species, where they found that the *B. subtilis, E. coli,* and *Salmonella typhi* species displayed excellent results because of their nanosize (Kumaresan et al., 2018). Rajaboopathi and Thambidurai (2018) synthesized silver nanoparticles using *Padina gymnospora* extract on cotton fabric. Upon testing, they found the fabric displayed higher inhibition against *S. aureus* and *E. coli* species, and had better UV protection efficiency (Rajaboopathi and Thambidurai, 2018). Afrin et al. (2023) selected six types of seaweeds (Padina tetrastromatica, Sargassum muticum, Hydroclathrus clathratus, Botryocladia wrightii, Porphyra, Gracilaria parvispora from St martin’s Island, Bangladesh) and studied their antibacterial, antioxidant properties and scavenging effects. They used methanolic (yield: 4.40 %–14.26 %), ethanolic (yield: 2.40 %–17.43 %), and acetone (yield: 1.50 %–4.53 %) to determine the extract yield of the different seaweed species where the highest yield was found in methanolic extracts of Sargassum muticum, Hydroclathrus clathratus, Porphyra, Gracilaria parvispora followed by ethanolic and acetone extract, respectively (Afrin et al., 2023).

4. Recent applications of antibacterial agents derived biomass

4.1. Biomedical

Biomass derivatives are available to be functionalized for medical applications. The non-toxic, biocompatible, and biodegradable properties are the main characteristics of biomass derivatives-based design for biomedical applications (Kumar et al., 2021). Lignin, tannin, chitosan, cellulose, and hemicellulose have gained increased industrial interest because of their particular features as antimicrobial, antioxidant, and biochemical properties which are caused by the presence of hydroxyl and carbonyl groups especially in lignin and tannin (Park et al., 2017). Liu et al. (2018b) studied the filler from lignin by ring-opening polymerization with D-lactide to the alkali lignin. This approach enhanced the stability and long-term release of trans-resveratrol. To encapsulate doxorubicin hydrochloride, Zhou et al. (2019) prepared a drug delivery platform derived from lignin by creating a layer-by-layer self-assembled system that incorporated folic acid and magnetic nanoparticles. This system showed low cytotoxicity due to the enhancing capacity in the cellular uptake against HeLa cells. Another work by Alqahtani et al. (2019) studied the application of lignin as an oral drug in the delivery system with curcumin as the drug model. As a natural polyphenolic compound, curcumin has low oral bioavailability and poor solubility but limited therapeutic efficacy. Therefore, this system suits drug molecules with limited bioavailability and low solubility. Furthermore, these derivatives of biomass are also potential wound dressings due to their antimicrobial, antidiabetic, and antioxidant activities and capacity to absorb water. Reesi et al. (2018) explored the electrostatic interaction between lignin-based nanofibers that surface-modified with arginine molecules as the agent for wound healing. The gel had a good spreadability and viscosity for topical administration, and the arginine release from the system was prolonged.

Cass and Burg (2012) evaluated the anticancer properties of tannin, released from biomaterials, as a drug delivery system. The gradual release of tannin over time has anticancer and chemotherapeutic properties. A collagen/tannin injectable hydrogel has been studied as a matrix for regenerative tissue and a chemotherapeutic agent for breast cancer (Cass and Burg, 2012). In addition, Ge et al. (2019) investigated the antimicrobial activity of hydrogels derived from polyvinyl alcohol-containing borax and cellulose nanofibrils in variable concentrations of tannin against *S. aureus*. The inhibition area enhanced from 4 to 7 mm with increasing tannin concentration. Then the diameter of the inhibition zone was more than doubled after the lowest concentration of tannin was added to the hydrogel. The antioxidant properties also increased as tannin hydrogel content increased (Ge et al., 2019). Intriguingly, the antioxidant and antibacterial activities of tannin hydrogel could be enhanced through thermal processing (Pyla et al., 2010; Xu et al., 2015). Ravishankar et al. (2019) studied the synthesis of chitosan combined with alkali lignin as a promising wound healing through ionotropic cross-linking. The 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl-2H-tetrazolium bromide (MTT) assay was employed to determine the cytotoxicity of the chitosan-alkali lignin hydrogels, which were found to be harmless. The hydrogels dramatically enhanced the capacity of cells to move around the scratch in a scratch test with the cell lines from mouse fibroblast (NIH 3T3). Another work that used chitosan came from Jaganathan et al. (2018), who prepared lignin-chitosan biocomposites via the freezing technique. Lignin was derived from the banana peel, and the biocomposites demonstrated biocompatible properties, thus exhibiting great antibacterial activity (Jaganathan et al., 2018).

In addition, the study from Ali et al. (2022) showed that the hydrogel created by the mixture of chitosan and hemicellulose is biocompatible over the long term and has better antioxidant, antimicrobial, and cell proliferation properties than its host polymer. According to a study by Bush et al. (2016), the hydrogels derived from xylose can be implemented as injectable substances and heal the wound. Due to their biocompatibility and adaptability, hydrogels derived from hemicellulose are also applicable as nanofibrous scaffolds in the tissue engineering of cardiac sections (Bush et al., 2016). Venugopal et al. (2013) synthesized nanofibrous scaffolds from the cross-linking of xylan and polyvinyl alcohol with glutaraldehyde as the cross-linking agent and tested on the rat neonatal cardiomyocytes. The outcome indicates that the scaffolds can promote the cardiomyocytes' proliferation and be utilized in tissue engineering from the cardiac section (Venugopal et al., 2013). Melandri et al. (2006) have shown that the dressings of hemicellulose can repair various lesions or diseases of the skin, thus, they are effective and safe as wound dressing. Many reports have been found for application seaweed as antibacterial agent in biomedical application. To get comprehensive review of this, the review from Narasimhan et al. (2023) is suggested to follow. Expanding studies regarding the use of biomass materials in medicine have been focused on the growth of interdisciplinary studies between medicine and bioengineering. The creation of superior and unique medicinal materials that combine clinical requirements and the physical properties of biomass is promising for use in biomedical applications. However, comprehensive laboratory work with in vivo and in vitro studies should be acknowledged due to the proof of safety in humans. In biomedical applications, biomass can act as an antimicrobial agent either as a single agent (lignin, tannin) or functionalized biomass (chitosan+lignin or chitosan+hemicellulose), the activity of which is influenced by the type of microbial target.

4.2. Textile

The use of biomass derivatives in coating materials for textiles as antibacterial agents has increased significantly in recent years. These biomass derivatives' antibacterial components can be utilized as growth inhibitors for dangerous microorganisms. One of these biomasses is formed from lignin and tannins, which have phenolic hydroxy groups that have antibacterial properties. Črešnar et al. (2022) found that the phenolic chemicals in lignin and tannins can harm bacterial cell membranes. Antibacterial textiles are becoming more and more prevalent in both medical and non-medical products. Various ways to apply antibacterial compounds with a variety of methods, including barriers, regeneration principles, and coating mechanisms. The most straightforward method is to simply cover the fabric with an antibacterial agent. The lignin solution reportedly remained stable for 60 days, allowing for its usage in production (Ugartondo et al., 2008). Additionally, biomass derivatives are frequently used as antibacterial agents in a variety of scientific applications. As in the study conducted by Sunthornvarabhas et al. (2017), lignin from sugarcane bagasse extract was applied to cloth to act as an antibacterial against *Staphylococcus epidermidis*. Dimethylsulfoxide was used to dissolve the powdered lignin extract, and ethanol was added to dry. Depending on the dose, lignin extract exhibited favorable antibacterial activity. Coated fabrics can be employed as a supplementary component of sanitizing masks because they don't significantly reduce pressure.

Bhushan et al. (2020) used the addition of mordants such as potassium alum, copper sulfate, and iron sulfate to bind lignin to fabrics. Lignin biomolecules extracted from peanuts using ultrasonic sonication technique showed significant antibacterial activity (79.7 %–86.3 %) against *S. aureus* and *E. coli* bacteria (Bhushan et al., 2020). In another report, Chen et al. (2022a) made Ag/lignin-coated nanoflowers with biomass lignin as a reducing and sealing agent. The liquid phase spray deposition method was used to apply Ag/lignin to the fabric, and the antibacterial activity was assessed using *E. coli* and *S. aureus* bacteria. After friction treatment and washing, it was discovered that the changed fabric inhibitory zone had an average diameter of 0.32 and 0.16 cm, respectively (Chen et al., 2022a).

Zhang et al. (2020) utilized novel tannic acid (TA) (hydrolyzable tannin) in the antibacterial application of silk materials through TA adsorption followed by iron salt mordant. The production of TA-ferrous complex ions was verified by Fourier transform infrared spectrometer (FT-IR) and UV-visible spectroscopic analysis. The modified fabric could fight against microorganisms like *S. aureus* and *E. coli* bacteria after 20 times of washing. Natural silk has a low bactericidal rate of about 22 %, however, the handled silk has a 95 % inhibitory rate. The modified fabric's antibacterial level remained greater, at 93 %, after 20 times of washing. The numerous phenolic hydroxyl groups in TA and the development of the ternary TA-Fe-silk chelating complex in the silk fiber are responsible for this exceptional washing resistance (Zhang et al., 2020). Additionally, Bu et al. (2018) studied viscose and superhydrophobic textiles that were developed through in situ growth of AgNP on TA coated viscose textiles and subsequent hydrophobic treatment under mild reaction conditions. These textiles were strong and after 50 washing cycles, they still exhibited exceptional antibacterial properties against *S. aureus* and *E. coli* bacteria because of their high bacterial absorption rate of over 97 %. Because of their capacity to chelate tannic acid and hence provide high washing power, AgNP is dispersed throughout and joined to TA-coated viscose textiles (Bu et al., 2018).

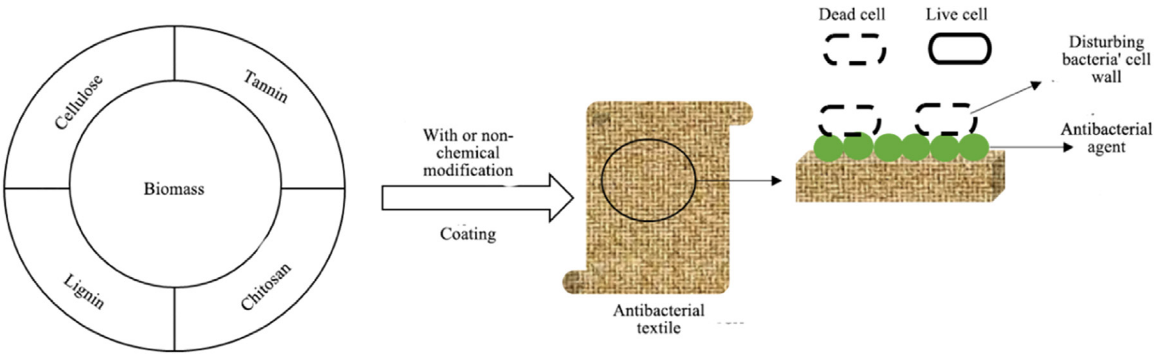


Fig. 12. Analogy of biomass derivatives application as an antibacterial agent.

The efficacy of chitosan isolated from *Aspergillus niger* for cotton textile application was proven against *E. coli* and *C. albicans* bacteria and the durability was tested ten times with stable antibacterial activity (Tayel et al., 2011). However, the durability of chitosan antibacterial activity during laundering was based on fiber characteristics and type of bacteria because, in silk application, poor durability after washing was detected on *E. bcoli* and stable for *S. aureus* (Ranganath and Sarkar, 2014).

Cellulose grafted with organosilane was coated on cotton fabric to create an antibacterial textile with 99.99 % antibacterial reduction against *S. aureus* and *E. coli*. Unlike tannin and lignin which have strong colors, an advantage of using cellulose derivatives is no color change of the textile after coating and the waterproofing and hydrophobic properties can be improved (Hongrattanavichit and Aht-Ong, 2021). To date, authors cannot find the utilization of hemicellulose or its derivatives as an antibacterial agent for textiles. Application biomass derivatives as antibacterial agents on textiles are illustrated in Fig. 12. Some researchers extracted seaweed as a natural color to create antibacterial textile by direct application (Janarthanan and Senthil Kumar, 2018; Rani, 2020) or combined with metal nanoparticles to enhance the durability (Bhutiya et al., 2018a; Rajaboopathi and Thambidurai, 2018). Polyphenol substances from biomass exhibit potential applications in textile industries as antibacterial additives. However, the dark color, low solubility in water, and poor durability are still a barrier to feasibility. Converting the macro size of polyphenol to colloidal particles may overcome this problem and this research topic needs to be explored.

4.3. Food industries

Recently, there has been changed a focus on food packaging from traditional to active packaging to ensure food quality. Active packaging qualities are focused on increasing the food commodities' shelf life from producers to consumers while maintaining food quality, nutrition, and flavor (Jayakumar et al., 2022). Active packaging contains active ingredients/materials that can act as antioxidants, oxygen scavengers, CO_2 emitters, ethylene absorbers, moisture controllers, and antimicrobials. Based on Davidson et al. (2013), antimicrobial agents ideally should inhibit a broad range of spoilage and pathogenic microbes, do not cause sensory changes in food, have low cost, and are nontoxic and effective at low dosages (Davidson et al., 2013).

Antimicrobial agents are divided into organic/natural antimicrobials and inorganic antimicrobials. Inorganic materials such as zinc oxide, silver, triclosan, copper, and silver zeolite are common active materials in commercially produced antimicrobial packaging products Firouz et al., 2021. Natural antimicrobials can originate from animals, plants, or microbes. There are so many antimicrobials agent based on plant sources such as essential oils (EOs) (Pandey et al., 2017; Ribeiro-Santos et al., 2017; da Costa et al., 2020; Amor et al., 2021), lignin (Alzagameem et al., 2019; El-Nemr et al., 2019), tannins (da Cruz et al., 2020; Li et al., 2022; Hidayati et al., 2023), pomegranate (Ali et al., 2019; Nur Hanani et al., 2019), and seaweed extract (Singh et al., 2018) which can incorporate with food packaging. Table 8 displays the recent development of natural antimicrobial agents in active packaging using various polymer matrices.

EOs can be derived from some plants, including oregano, basil, clove, thyme, and eucalyptus. EOs may limit the growth of bacteria that are both Gram-negative and Gram-positive. The main components of EOs in charge of antimicrobial activity are phenols, aldehydes, ketones, and oxygenated terpenoids (Mousavi Khaneghah et al., 2018; El-Saber Batiha et al., 2021). Their hydrophobic properties also play a crucial part in interacting with lipids of the cell membrane and mitochondria of microbes. As a result, it reduces the configuration of the bacteria structures, increasing their permeability and breaking down the cell membrane (Mousavi Khaneghah et al., 2018). Some researchers have tried to combine the EOs with some polymer matrix such as polylactic acid (PLA) (Salmieri et al., 2014; Subbuvel and Kavan, 2022), polybutylene adipate-co-terephthalate (Sharma et al., 2020), poly(hydroxybutyrate-co-hydroxy valerate) (da Costa et al., 2020), chitosan (Amor et al., 2021), polyethylene terephthalate (PET)(Konuk Takma and Korel, 2019), and starch (Souza et al., 2021; Chen et al., 2022b). The high boiling points of EOs (>200 °C) makes them appropriate to combine with various polymer matrices without forfeiting their characteristics (Maisanaba et al., 2017). However, according to Salmieri et al. (2014), PLA-cellulose nanocrystal incorporated with oregano EOs reduced the mechanical strength of the film even though they have great antimicrobial activity. A high EOs concentration is necessary to have a substantial impact on bacteria (Vilela et al., 2018). EOs are volatile materials that evaporate easily in ambient atmospheres, limiting the antibacterial effectiveness of EOs-based active packaging and potentially affecting the smell and taste of food products Firouz et al., 2021. Further investigation is needed to produce

Table 8
The recent development of natural antimicrobial agents in active packaging using various polymer matrices.

Polymer matrix	Antimicrobial agent	Inhibited microorganism	Reference
Poly(hydroxybutyrate-co-hydroxy valerate)	Oregano essential oils (EOs)	*S. aureus* and *E. coli*	da Costa et al., 2020
Chitosan	Basil EOs	*S. saprophyticus* and *E. coli*	Amor et al., 2021
Polybutylene adipate-co-terephthalate and polylactic acid	Clove and thyme EOs	*S. aureus* and *E. coli*	Sharma et al., 2020
Polylactic acid/corn starch	Eucalyptus leaf EOs	Trichoderma, *S. aureus*, and *E. coli*	Chen and Chien, 2022
Polyethylene	Black cumin EOs	*E. coli*	Konuk Takma and Korel, 2019
Polylactic acid	Fenugreek EOs and curcumin	*S. aureus* and *E. coli*	Subbuvel and Kavan, 2022
Cellulose-chitosan	Lignin	*B. thermosphacta* and *P. fluorescen*	Alzagameem et al., 2019
Cationic wood nanofiber	Lignin	*S. aureus* and *E. coli*	Sirviö et al., 2020
Polylactic acid	Lignin	*B. circulans*	Chaubey et al., 2020
Polyvinyl alcohol-gelatin	Lignin	*S. aureus, B. subtilis, P. aeruginosa,* and *E. coli*	El-Nemr et al., 2019
Polyvinyl alcohol	Cationic tannins	*S. aureus* and *P. aeruginosa*	da Cruz et al., 2020
Gelatin-cellulose nanocrystals	Nonoxidized tannic acid	*S. aureus* and *E. coli*	Leite et al., 2021
Glycerol-cornstarch	Tannic acid	*S. aureus*	Ma et al., 2022
Sodium alginate	Tannic Acid	*E. coli*	Li et al., 2022
Chitosan	Tannic acid	*S. aureus* and *E. coli*	Lee et al., 2023
Starch-polycarprolactone	Pomegranate peel	*S. aureus*	Khalid et al., 2018
Starch	Pomegranate peel	*S. aureus* and *Salmonella*	Ali et al., 2019
Fish gelatin	Pomegranate peel	*S. aureus, L. monocytogenes*, and *E. coli*	Nur Hanani et al., 2019
Nanofibrillated cellulose	Brewers spent grain arabinoxylan	*S. aureus, E. coli*, and *C. albicans*	Moreirinha et al., 2020
Polyvinyl alcohol-gelatin	Amaranthus leaf extract	*B. cereus* and *S. aureus*	Kanatt, 2020
Cellulose acetate	Sodium alginate and carageenan extracted from *S.wightii/G. corticate*	E. coli, S. aureus, and P. syringae	Rajeswari et al., 2020
Ulva ohnoi extracted cellulose	ZnO nanoparticles and curcumin	*B. cereus, S. aureus, L. monocytogenes, E. coli, S. typhimurium*, and *V. parahaemolyticus*	Saedi et al., 2023
Polyvinyl alcohol/ red seaweed extracted cellulose nanocrystal	Basil leaf extract	*L. monocytogenes* and *B. cereus*	Singh et al., 2018
Kappaphycus alvarezzi/cinnamon nanoparticles	Red seaweed/cinnamon nanoparticles	*E. coli, S. aureus*, and *Salmonella*	Rizal et al., 2023

Notes: EOs, essential oils; S. saprophyticus, Staphylococcus saprophyticus; P. fluorescens, Pseudomonas fluorescens; B. circulans, Bacillus circulans; P. Syringae, Pseudomonas syringae; V. parahaemolyticus, Vibrio parahaemolyticus.

antimicrobial packaging that uses EOs as the active agent, which has good mechanical qualities without affecting the organoleptic qualities of food.

Lignin is a biopolymer with high potential as an active material in food packaging due to its antibacterial, antioxidant, and UV-blocking abilities (Tavares et al., 2018; Ariyanta et al., 2023b). The lignin's phenolic hydroxyl groups are the primary compound that contributes to those abilities (Guo et al., 2019). However, lignin has difficult compatibility with polymer matrix because of the hydrophobicity of lignin. Due to its hydrophobicity, lignin has issues interacting with polymer matrix. Some researchers change the lignin structure using chemical or physical modifications to improve compatibility (He et al., 2019). Lignin modification through size reduction into nanoparticles could enhance the thermal and mechanical properties of the film, enhancing the antioxidant activity, and also improving the antimicrobial activity because of the expanding contact area between lignin and bacteria's surface (Yang et al., 2016; Jayakumar et al., 2022). Chemical modification through lignosulfonate-calcium was conducted by Hu et al. (2016) to strengthen the interaction between lignin and poly vinyl alcohol (PVA) matrix. The findings indicated that lignin could be dispersed more homogeneously, which makes the film more thermally stable and miscible (Hu et al., 2016). The antimicrobial activity of lignin in film packaging is also influenced by the raw material and the isolation methods. Alzagameem et al. (2019) examined three varieties of kraft lignin from softwood, organosolv lignin from softwood, and organosolv lignin from grass as active material in the chitosan matrix. The results proved that organosolv lignin from softwood got the highest antimicrobial and antioxidant activity, followed by kraft lignin from softwood and organosolv lignin from grass (Alzagameem et al., 2019).

TA is a phenolic compound from plant extract. The bioactive make TA has various potentials as an antioxidant, antimicrobial agent, and UV blocking. TA contains five gallol and five catechol, which can interact with numerous biopolymers by intermolecular hydrogen bonding and cross-linking (Li et al., 2022; Lee et al., 2023). As a result, tannin can improve the water vapor barrier of the film (Li et al., 2022) but not the mechanical properties. Adding TA to the polymer matrix cannot improve the mechanical strength significantly. To improve the mechanical strength, TA must be cross-linked by covalent bonding (Yuan et al., 2021). Pomegranate was reported as a potential antibacterial agent in active packaging (Khalid et al., 2018; Ali et al., 2019; Nur Hanani et al., 2019; Chen et al., 2020). Pomegranate skin contains polyphenols and tannins that are responsible for the antibacterial action (Khalid et al., 2018).

Fig. 13. System development of active packaging using antimicrobial agents by different methods (Kanmani and Rhim, 2014).

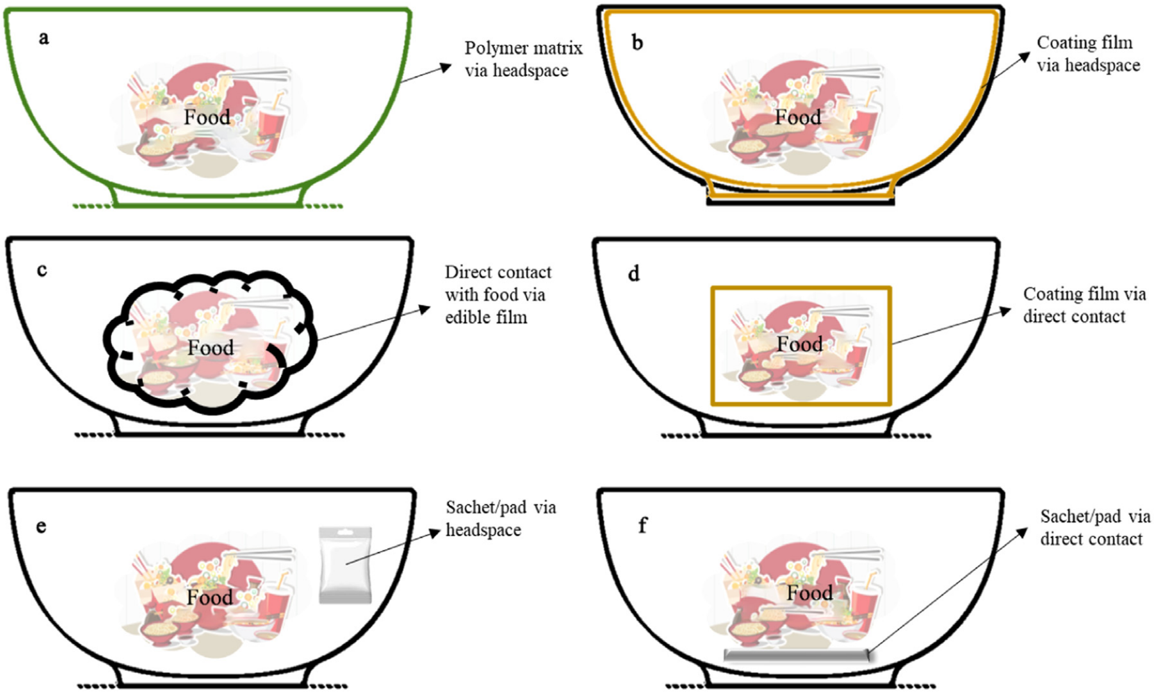


Fig. 14. The illustration of antimicrobial agents being applied in the food packaging (Mousavi Khaneghah et al., 2018).

Antimicrobial active packaging systems can be developed using various formations of antimicrobial agents and polymer matrices (Fig. 13) (Kanmani and Rhim, 2014). There are two types of antimicrobial active packaging: active releasing material and nonmigratory material. Active releasing material contains volatile compounds into the headspace of packaging or can control the migration of non-volatile compounds; nonmigratory material can perform without migration. The illustration of antimicrobial agents being applied in the packaging is shown in Fig. 14 (Mousavi Khaneghah et al., 2018). The detailed explanation can be divided into three methods (Kapetanakou and Skandamis, 2016). The first method involves the application of volatile chemicals in various carriers such as pads, pounces, or sachets. The method relies on evaporation in the headspace of the package without any interaction with food (Fig 14e). The second approach involves the introduction of an antimicrobial agent (volatile or non-volatile) into a polymer (edible or not) via indirect contact. The mechanism relies on diffusion (non-volatile compound) or vapor release in the packaging's headspace (volatile compound) (Fig 14a, b, and f). In the third approach, antimicrobial chemicals (volatile and/or non-volatile) are applied directly to

Table 9
Potency biomass compounds in cosmetic applications with the properties.

Biomass/biomass derivates	Main active compound	Property	Reference
Lignin	Mycosporine, such as amino acids, phenolic acids, flavonoids, and phenolic compound	Anti-aging, antimicrobial, anti-inflammatory, natural cosmetic, sunscreen, whitening, and wound treatment	Ariyanta et al., 2023a
Stingless bee (*Tetragonula biroi*)	Methyldiplacone, nymphaeol A, and 5,7,3′,4′-tetrahydroxy-6-geranyl flavonol	Antioxidant, anti-inflammatory, scavenging properties, and anti-acne activities	Arung et al., 2023
Eupatorium plants active constituents	Sesquiterpenes, phenolics, polysaccharides, and pyrrolizidine alkaloids	Anti-oxidant, anti-tyrosinase, melanogenesis/anti-melanin, anti-inflammatory, and anti-acne	Putri et al., 2022
Pectin	Pectin coordinates with calcium, pectin alginate microspheres	Antibacterial property, gelling, emulsifying, thickening, coloring, and stabilizing agent	Thakur et al., 1997; Dhat et al., 2009; Chetouani et al., 2017
Agar	Chlorogenic acid, phenolic acids, and flavanols	Antioxidant, antimicrobial, and antifungal activity; anti-inflammatory, anti-obesity, anti-aging, anti-tumour, hepatoprotective activity, and prebiotic effects	Oliveira et al., 2021; Vasyliev et al., 2022
Cellulose	Cellulosic fibers, hydrated calcium oxalate; plant extracts (such as *Matricaria chamomilla, Calendula officinalis, Aloe vera*) and essential oils (*Lavandula officinalis, Cinnamomum zeylanicum, Melaleuca alternifolia,*) with methylparaben	Antimicrobial properties, UV protection, anti-inflammatory, antioxidant, mild tyrosinase inhibition, antibacterial activities, softness, facial masks, and hygroscopic properties	Thombare et al., 2016; Kozlowska et al., 2019
Chitosan	Pectin alginate, N-acetyl glucosamine, 2-amino-2-deoxy-β-D-glucopyranose, and D-glucuronic acid	Antibacterial, hair conditioning, skin fixative, biodegradable, antibacterial as wound dressing agent	Chetouani et al., 2017; Sionkowska et al., 2020
Tannin	Polyphenol, mainly condensed tannins, and tannic acid	Mainly absorbs UV-B rays, and has anti-inflammatory activity, a strong antioxidant, radical scavenging properties, anti-acne, anti-redness, anti-aging, anti-wrinkle antiastringent, wound healing characteristics, and antibacterial. Applied in boost synergy activities sunscreen formulation, eliminating excess oil from pores, improving skin's texture and tone.	Pizzi, 2008; Alfonsi et al., 2023
Seaweed (brown/red/green algae)	Sodium alginate from brown algae, carrageenan from red algae, ulvan polysaccharide from green algae *Ulva rigida* and curcumin	Antioxidant and antimicrobial	Selvasudha et al., 2023
Seaweed cellulose (*Ulva fasciata*)	Extracted cellulose from seaweed/Zno nanorod clusters	Antimicrobial	Bhutiya et al., 2018b

the food by coating or edible film. The diffusion approach is used in the mechanism (Fig 14c and d). Ultimately, the most recent scholarly discoveries may herald a breakthrough in the field of food packaging, ushering in a new era of sustainable, customized, and environmentally friendly packaging options. However, as a substance contact directly or indirectly with human consumption, in vitro, in vivo, and migration studies should also be conducted due to safety concerns.

4.4. Cosmetics

The largest number of cosmetic products are produced by Europe with the largest contributions from France and Germany which along with the UK, accounts for almost 78.6 billion Euro, followed by the USA (67.2 billion Euro). The European nations are also considered global markets for the cosmetic industry with an average consumer expenditure of about 135 to 225 Euro per person per year (Cosmetics-Europe, 2019) which is growing at a high rate forecasted to reach approximately 98.7 billion Euro by 2026. However, the cosmetics industry nowadays faces numerous challenges because of cost, usage of synthetic chemicals, packaging problems, non-availability of raw materials at a cheaper price, non-biodegradable nature, pollution of the environment, ban of certain toxic chemicals, health and safety levels, environmental legislations, and changing market trends (Adeola, 2021).

Industrial investments are increasingly focused on developing eco-friendly solutions that replace synthetic ingredients with natural materials. Bioactive substances and natural biopolymers are currently used in cosmetics, skincare, and health monitoring goods to address the high demand for protective care and therapeutic products (Chourmouziadi Laleni et al., 2021; Tarassoli et al., 2021;

Meftahi et al., 2022). These organic components promote the skin's defence, recovery, thermoregulation, and immunological mechanisms (Aguilar-Toalá et al., 2019).

The skin provides the first layer of protection against exposure to physical, microbial, chemical threats, and environmental (Fernandéz et al., 2016). Health hazards, including threats to the skin itself, can result from the attachment of microbes to the skin contact surface. There is evidence that harmful germs can cling to both non-contact surfaces and skin contact (Abo-elmaaty et al., 2016), which can lead to acne and skin inflammation. An antibacterial agent was created to address the issue because microbial colonization contributes to the emergence of acne (Yurdasiper et al., 2022). *Acne vulgaris* is a pathological condition caused by the anaerobic Gram-positive bacterium such as *Cutibacterium acnes* (*C. acnes*) (Yurdasiper et al., 2022). The finding demonstrates that *Propionibacterium acnes* (*P. acnes*), an anaerobic Gram-positive bacterium that dwells in follicles and on the skin surface, is the primary cause of inflammatory lesions in *Acne vulgaris* (Wei et al., 2021). Typical therapeutic agents for *P. acnes* and *C. acnes*-induced inflammatory skin diseases, such as tetracycline and adapalene, are antibiotics (Wei et al., 2021). Their excessive use, however, could result in harmful side effects such as skin irritability and bacterial resistance. Therefore, it is critical to look for alternatives with antibacterial properties but no adverse effects. Phytochemical remedies, such as flavonoids, saponins, and panaxynol, have been proved effective in treating acne due to their powerful antibacterial properties and security.

Saponin fractions (SFM) from aqueous extract of *Sapindus mukorossi* (*S. mukorossi*) were isolated and evaluated for antibacterial activity against *P. acnes* (Wei et al., 2021) using semi-preparative high-performance liquid chromatography (HPLC). The SFM showed higher antibacterial activity than the water fraction of *S. mukorossi* (WFM), indicating the effectiveness of semi-preparative HPLC in purifying bioactive chemical compounds from *S. mukorossi*. WFM and SFM were applied to wash and past masks in a 0.3–0.4 mg/mL concentration range, and they displayed a uniform texture, good antibacterial properties, and an acceptable drying time. SFM displayed higher activity than WFM and was successful in decolorizing, overcoming the drawback of WFM's dark color. Furthermore, another study reported that the *Sapindus saponins*, Sapindoside A and Sapindoside B, from *S. mukorossi*, synergistically disrupted *C. acnes* by altering ultrastructural morphology and membrane composition (Wei et al., 2021). This could be achieved through membrane permeability enhancement and the destruction of the bacterial envelope. Molecular docking confirmed that Sapindoside A played a more significant role than Sapindoside B in their synergistic combination, as it showed a higher score interaction with penicillin-binding protein 2. This protein is crucial for the cross-wall's peptidoglycan synthesis, indicating that Sapindoside A contributed more to the synergistic accomplishment of membrane proteins. Further, Table 9 displays recent potential bioactive substances from biomass that possess antibacterial properties for use in cosmetics applications. Biomass applications for cosmetics are more diverse, involving a combination of several activities such as anti-aging, antimicrobial, whitening, anti-acne, or as emulsifier. Nevertheless, the toxicity and dermal skin irritation test regarding the natural antibacterial compound from biomass needs to be investigated. Besides, the dermatological test of these active substances is required to be applied in cosmetics. Inclusive studies about these matters are still limited.

5. Conclusion, challenges, and future prospectives

Current studies showed the potency of environmentally benign antibacterial agents, such as tannin, lignin, cellulose, hemicellulose, and chitosan, derived from biomass both wood and non-wood (such as marine biomass). The number of papers that worked on the keyword "biomass as antibacterial agent" increased notably per year since the last decade (20 publications in 2013 to 110 publications in 2023) in the Scopus portal accessed on August 10th 2023. Polyphenol types in biomass (lignin and tannin) with or without functionalization are known effective in combatting bacteria growth. Meanwhile, the primary compounds of biomass, polysaccharides, are usually used as an antibacterial agent after the chemical modification, especially cellulose. Antibacterial properties of biomass depend on types of bacteria, chemical structure, concentration, extraction method, and chemical modification. In general, biomass derivatives can inhibit Gram-positive and Gram-negative bacteria. Unlike lignin, tannin, hemicellulose, and chitosan which can directly be applied as an antibacterial agent, the structure of cellulose should be modified. However, the main advantage of cellulose as an antibacterial agent is colorless and high stability compared to other biomass derivatives.

The challenge of applying antibacterial agents from biomass is the strong color of the compounds and hydrophobicity. For instance, lignin and tannin as polyphenol compounds are known as effective substances in inhibiting the growth of bacteria yet the strong brownish color created color changes in the product after application. On the other hand, a colorless biomass substance, cellulose, needs more effort due to the needed chemical modification. Creating water-soluble biomass derivatives is a challenge because they might be more applicable on an industrial scale and need lower production costs. Another challenge is in vitro and in vivo studies of these compounds are still limited and should be conducted. In addition, dermatological test is still limited, particularly in cosmetics scopes. These research gaps should be filled in the future to make feasible applications of biomass derivatives as antibacterial agents.

With the introduction of the sustainability concept, the practice of applying natural-based materials to satisfy existing needs without sacrificing future demands has become a top priority. The usage of biomass materials has upsurged in recent years, owing primarily to their qualities of high supply, environmental friendliness, derived from renewable resources, and biodegradability. Therefore, biomass derivatives can potentially be used on the industrial scale to substitute fossil-fuel-based material for sustainable living. By revealing the full scope of the antibacterial capabilities of biomass, new knowledge bridges will be established across the fields of social to natural science, including the management of biomass supply to bioprocess.

Declaration of competing interest

The authors declare no conflict of interest.

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