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Anti-Biofilm Efficacy of Diverse Plant Extracts against Microbial Species: A Review

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Abstract

Microbial biofilms, composed of extracellular polymeric substances (EPS), pose significant threats to food safety, healthcare systems, and industrial environments due to their resistance to conventional antimicrobial treatments. These biofilms are protective barriers for pathogens, contributing to persistent infections and contamination challenges. The escalating concern of antibiotic resistance necessitates exploring alternative strategies, with plant-derived bioactive compounds emerging as promising candidates. This review critically examines the antibiofilm efficacy of diverse plant extracts, focusing on their mechanisms of action, including the inhibition of exopolysaccharide synthesis, extracellular matrix disruption, and interference with microbial adhesion. Through an extensive analysis of recent studies, this review highlights the potent antibiofilm properties of phytochemicals such as flavonoids, alkaloids, terpenoids, and essential oils, positioning plant-based antimicrobials as sustainable and effective alternatives for biofilm management. The findings underscore the potential of plant extracts in developing innovative strategies for controlling biofilm-associated infections in medical, food, and environmental applications.

Keywords: Biofilm formation, Antibiofilm activity, Microbial resistance, Plant-derived antimicrobials, Phytochemicals

Introduction

Microbial biofilms represent a significant challenge in healthcare, food processing, and environmental systems due to their inherent resistance to antibiotics and disinfectants. These structured microbial communities are encased in self-produced extracellular polymeric substances (EPS), enabling them to withstand harsh environmental conditions, evade host immune responses, and persist on various surfaces, including medical implants, food processing equipment, and industrial pipelines (1, 2). The World Health Organization (WHO) estimates that foodborne pathogens alone contribute to approximately 420,000 deaths annually, with biofilm-forming bacteria such as *Escherichia coli, Listeria monocytogenes, Salmonella enteritidis, and Pseudomonas aeruginosa* playing a significant role in contamination and disease outbreaks (3, 4).

Antibiotics have historically been the cornerstone of microbial infection control; however, the emergence of multidrug-resistant (MDR) strains has rendered many conventional treatments ineffective (5). The persistent nature of biofilms further exacerbates this issue, as cells embedded within these structures exhibit altered metabolic activity and express resistance genes, reducing the efficacy of antimicrobial agents (6). Consequently, there is an urgent need for alternative biofilm control strategies that circumvent the limitations of conventional antibiotics.

Plant-derived bioactive compounds have garnered increasing interest due to their broad-spectrum antimicrobial properties and ability to disrupt biofilm integrity (7, 8). Phytochemicals such as flavonoids, alkaloids, terpenoids, tannins, and essential oils have demonstrated significant antibiofilm potential by targeting key biofilm-forming mechanisms, including quorum sensing inhibition,

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extracellular matrix degradation, and microbial adhesion interference (9, 10). Recent research suggests that plant extracts can effectively combat biofilm-associated infections in clinical settings and mitigate contamination risks in food and water systems (11).

This review provides a comprehensive analysis of the antibiofilm efficacy of various plant extracts, emphasizing their mechanisms of action, bioactive components, and potential applications in healthcare and industrial settings. By consolidating findings from bibliometric analyses and experimental studies, this review highlights plant-derived antibiofilm agents as viable alternatives for microbial control and infection prevention.

Bibliometric analysis

Bibliometric analysis is a valuable tool for assessing research trends, citation patterns, and the overall impact of scientific literature within a specific domain. This approach enables a systematic evaluation of the development and progression of research in antibiofilm plant extracts. Bibliometric studies provide insights into the evolution of scientific inquiry and emerging research frontiers by analyzing publication trends, co-authorship networks, and keyword distributions. In this review, bibliometric analysis was conducted using data retrieved from Web of Science (WOS) and Scopus, two of the most comprehensive and widely recognized databases for scientific literature. The search query (biofilm AND plant AND antibiofilm) was employed to extract relevant articles published between 2020 and 2024. A total of 1,377 documents from Scopus and 707 from WOS were identified and analyzed using the bibliometrix R-package (Version 4.4.2), an open-source tool designed explicitly for bibliometric studies (12–14). The data from these versatile databases revealed that many publications with annual increases and different document types are depicted in (Fig 1). The country-wise documentation count showed India, Brazil, and China as the top 3 countries with many articles (Table 1, and Fig 2).

The bibliometric analysis revealed a significant increase in publications related to biofilm control using plant-derived compounds over the past five years. Figure 1 illustrates the annual publication trends, indicating a consistent rise in research output. A country-wise assessment (Figure 2) also highlighted that India, Brazil, and China lead in publication contributions, demonstrating strong academic interest in exploring plant-based antibiofilm strategies (Table 1).

Future researchers can leverage these findings to identify key research hotspots, explore high-impact studies, and establish collaborative networks in natural anti-biofilm agents. The results from this bibliometric assessment provide a structured framework for future investigations, facilitating the development of novel plant-based solutions for biofilm-related challenges across

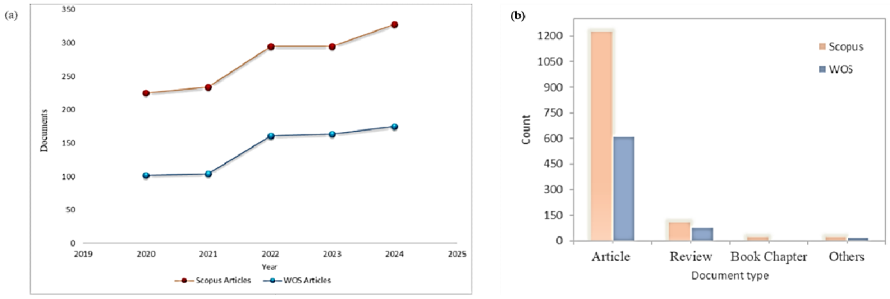

Fig. 1: The bibliometric analysis of documents from Scopus and WOS using biblioshiny R package; (a) Annual publication retrieved based on keyword (biofilm AND plant AND antibiofilm) from 2020-2024 (Dated as 26.12.2024); (b) Counts as per data type.

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healthcare, food safety, and environmental sectors.

Bioactivity of Plant Extracts *Antimicrobial Properties*

In recent decades, the introduction of antibiotics has revolutionized healthcare by preventing many life-threatening infections. However, these drugs' indiscriminate and sometimes unsystematic use—especially in developing regions—has contributed to the growing problem of antimicrobial resistance (AMR) (15). Much of the current research on AMR has focused on synthetic drugs, but there is an increasing interest in exploring natural antimicrobial compounds (Fig. 3). As a result, researchers have been investigating both aqueous and non-aqueous extracts from various parts of plants (seeds, leaves, roots, and trunks) for their ability to inhibit infection-causing microorganisms (16).

For instance, studies have evaluated mango extracts for activity against microbes such as *Bacillus cereus*, *Penicillium* species, *Fusarium* species, and *Escherichia coli*. The minimum inhibitory concentration (MIC) needed to suppress *B. cereus* ranged from 0.10% to 0.15%, whereas *E. coli* was more resistant (17, 18). Similarly, extracts from *Moringa oleifera* (drumstick) have been noted not only for their broad spread therapeutic properties including anti-inflammatory, antioxidant, antiulcer, antidiabetic, antitumor, and antipyretic effects—but also for their robust antimicrobial activity. In one study, an aqueous extract of *M. oleifera* roots effectively inhibited pathogens such as *Proteus mirabilis*, *Candida albicans*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *E. coli*, and *Aspergillus niger* (19).

Antibacterial Properties

Over recent decades, the appearance of multi-drug-resistant bacterial strains has spurred extensive research into both natural and synthetic antibacterial agents. In this context, plant extracts have shown exceptional promise against various pathogenic bacteria (20). Phytochemicals isolated from different plant parts have contributed significantly to developing pharmacological products for treating human diseases. For example, leaf extracts from *Azadirachta indica* (neem) have demonstrated inhibitory effects against a range of both gram-positive and gram-negative bacteria—including *Micrococcus glumtamicus*, *Bacillus stearothermophilus*, *Lactobacillus bulgaris*, *E. coli*, *Streptococcus faecalis*, *Micrococcus luteus*, *Bacillus cereus*,

Table 1: Top 10 countries holding the highest number of publications

Rank	Scopus		WOS	
	Country	NOP	Country	NOP
1	India	269	India	137
2	Brazil	118	Brazil	58
3	China	110	China	47
4	Egypt	74	Italy	39
5	Italy	58	Saudi Arabia	32
6	Iran	55	Iran	29
7	Korea	52	Korea	26
8	Saudi Arabia	51	Egypt	25
9	Pakistan	42	Pakistan	24
10	Turkey	41	South Africa	20

*Document search in both databases limited to 2020-2024; NOP: number of publications; WOS: Web of Sciences. Keyword – (biofilm AND plant AND antibiofilm)

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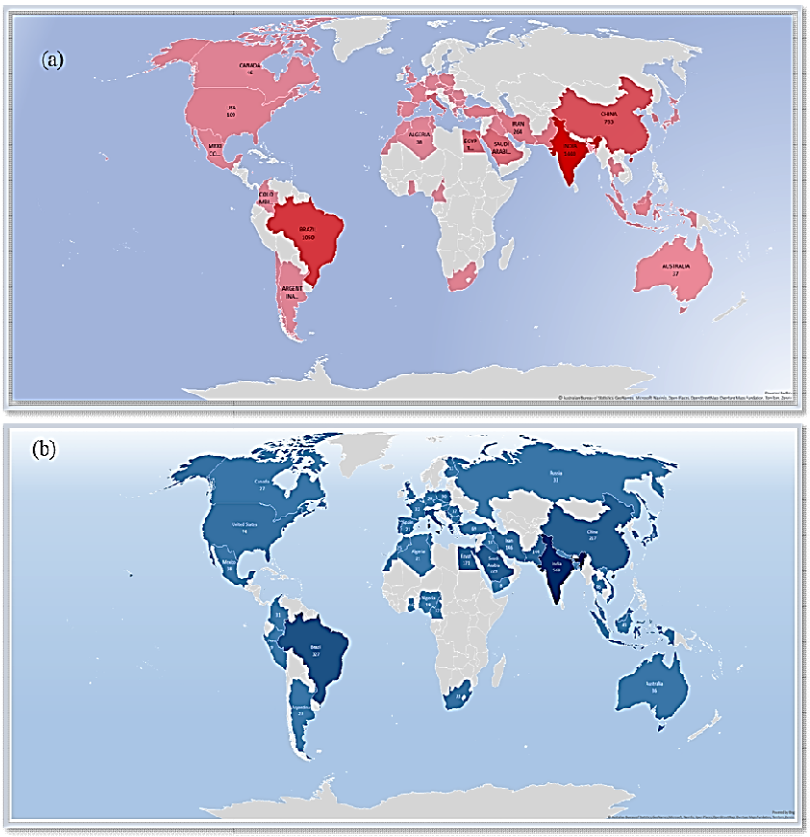

Fig. 2: Countries scientific production (a) Scopus & (b) WOS

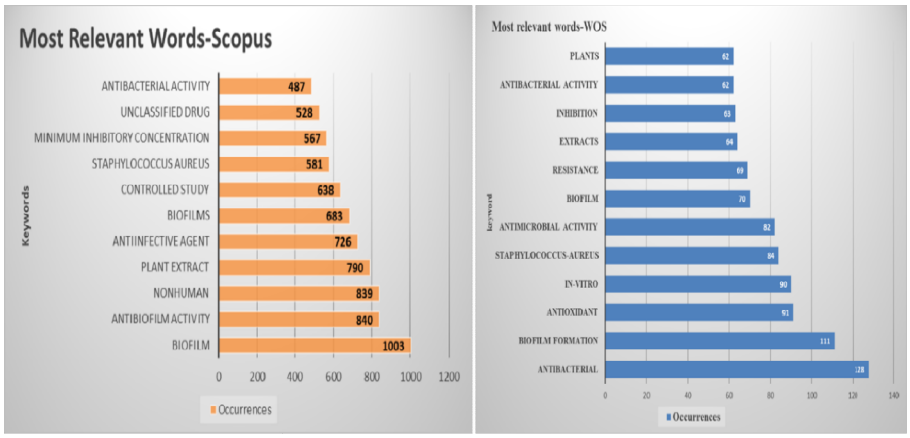

Fig. 3: Most relevant words

Plant Extracts against Microbial Species

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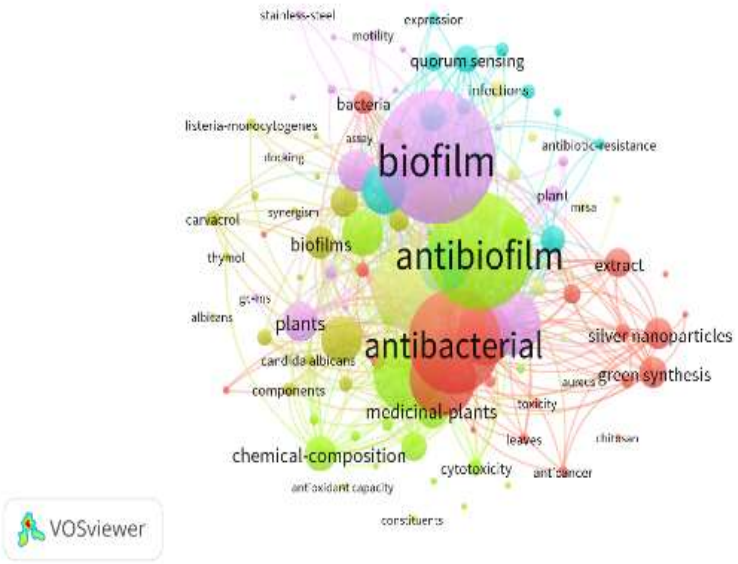

Fig. 4: Network visualization of co-occurrence of keywords from WOS using VOS viewer

and *Pseudomonas aeruginosa* (21, 22). Additional studies have confirmed that extracts from the fruit and leaves of *Phyllanthus emblica* also possess antibacterial properties (23). In contrast, crude extracts from the leaves and roots of *Psidium guajava* have been found effective against *E. coli*, *Klebsiella pneumoniae*, *Streptococcus pneumoniae*, and *Staphylococcus aureus* (24). Historically, plants have played a critical role in developing natural antibacterial agents, and ongoing research continues to emphasize their potential for creating safer medications (Fig. 4).

Antifungal Properties

Traditional antifungal medications were often developed to manage plant diseases caused by fungi. With increasing concerns over synthetic biocontrol agents' adverse environmental and health effects, there is a growing trend toward using botanical derivatives as safer, eco-friendly alternatives. Plants offer a rich source of natural compounds that exhibit antifungal activity, as evidenced by numerous studies on both human and plant pathogens. For example, neem leaf extracts have been effective against fungi such as *Epidermophyton*, *Candida*, *Geotrichum*, *Microsporum*, *Trichosporon*, and *Trichophyton* (25). In vitro experiments have also shown that ethanolic neem leaf extracts can inhibit the growth of *Penicillium expansum* (26). Furthermore, research into *Moringa oleifera* leaf extracts has revealed antifungal activity against soil-borne fungi such as *Fusarium*, *Pythium*, and *Rhizoctonia*, indicating its potential use as a natural fungicide (27). In addition to these antimicrobial effects, many plant secondary metabolites have been found to interfere with biofilm formation—a topic discussed in the next section (Fig. 5).

Antibiofilm Activity

A significant body of research has focused on how natural antimicrobial compounds can influence the survival and proliferation of microorganisms within biofilms. These investigations are particularly

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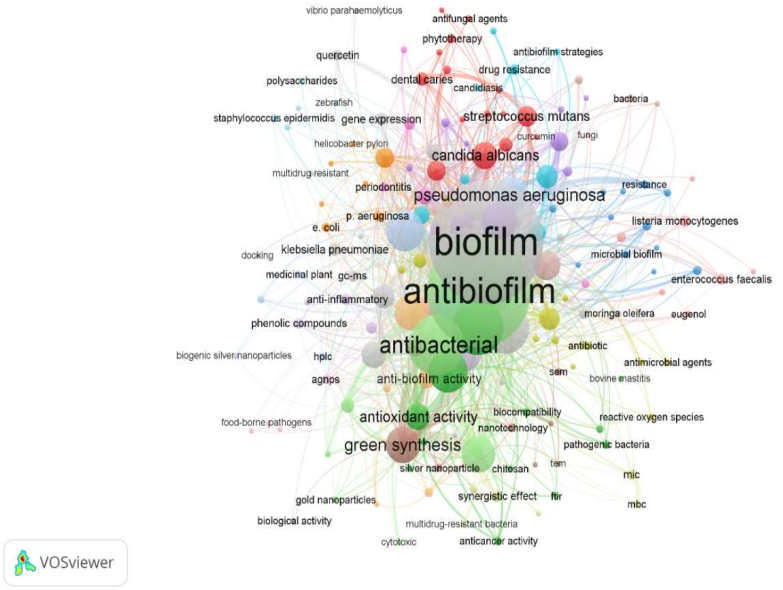

Fig. 5: Network visualization of co-occurrence of keywords from Scopus using VOS viewer

important in the food industry, medical devices, and water systems, where biofilm formation can increase antimicrobial resistance. This resistance is attributed to the reduced metabolic activity of cells within biofilms and the limited penetration of antibiotics, compounded by the expression of specific resistance genes. Consequently, there is an urgent need for new strategies to develop agents that can effectively disrupt biofilms.

Effective antibiofilm agents prevent free-floating (planktonic) cells from attaching to surfaces and forming structured biofilms. They achieve this by interfering with cellular adhesion, disrupting quorum sensing (the cell-to-cell communication system), and breaking down the established three-dimensional architecture of the biofilm (28). Numerous studies have employed both natural and synthetic compounds to counteract biofilm formation (Fig. 6). For example, research has shown that uropathogenic *E. coli* biofilms in urinary catheter environments can be disrupted by trans-cinnamaldehyde, coumaric acid, and ferulic acid. Trans-cinnamaldehyde was effective across all tested concentrations, while p-coumaric acid showed significant biofilm prevention even at low concentrations (0.25% and 0.5%), suggesting its potential for preventing urinary tract infections (29).

In another study, *Helicobacter pylori*—a bacterium implicated in chronic gastritis, gastroesophageal disorders, and peptic ulcers—was inhibited at an MIC of 16 µg/ml. Remarkably, reducing the concentration to half of the MIC resulted in an 82.3% decrease in biofilm formation, underscoring the potential of agents like curcumin. Known for its antibacterial, antifungal, anti-inflammatory, and antioxidant possessions, curcumin has emerged as a promising candidate for treating *H. pylori* infections (30, 31).

Additionally, *Candida albicans*, a fungal pathogen notorious for forming biofilms on medical devices, has been targeted using tertrandine—an alkaloid that inhibits its hyphal development. At 32 mg/ml concentrations, tertrandine could eradicate up to 60% of the fungal biofilm (32). Advances in

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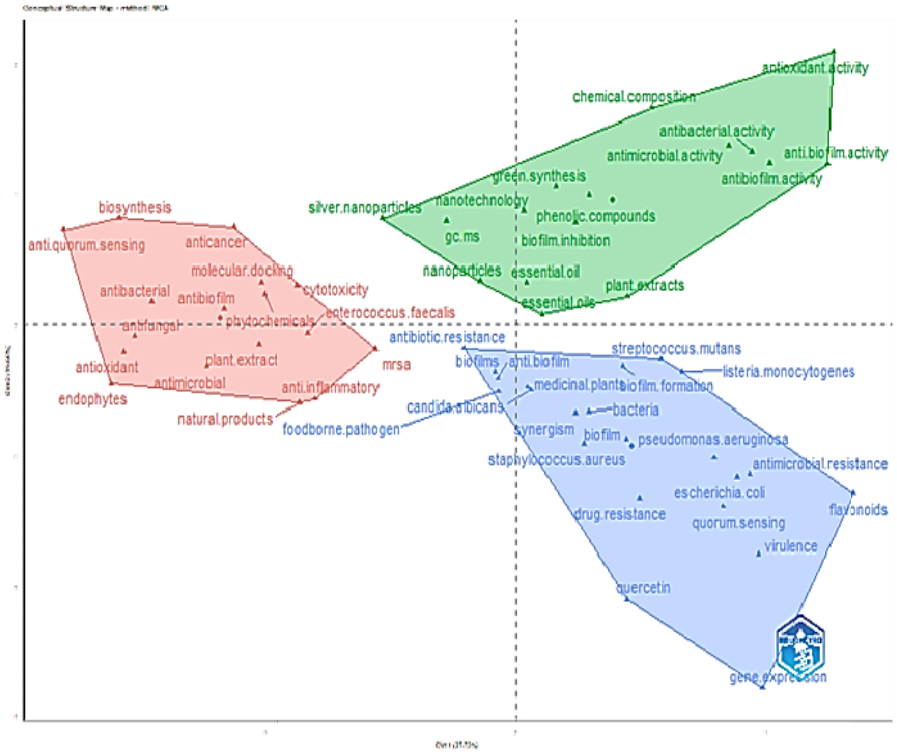

Fig 6: Conceptual structure map of all keywords

nanotechnology have further contributed to this field; nanoparticles made of materials such as silver, gold, zinc oxide, and magnesium fluoride have shown considerable efficacy in inhibiting biofilm formation. For example, crystalline magnesium fluoride nanoparticles synthesized via microwave techniques significantly reduced biofilm formation by *E. coli* and *S. aureus*, while gold nanoparticles lowered the hydrophobicity index of *S. aureus* by 78% and *Vibrio harveyii* by 46%. Other studies have indicated that adding sugars can enhance *E. coli* biofilm growth on various surfaces (e.g., polystyrene, polypropylene, glass, and stainless steel) (Fig. 7). In contrast, compounds like cyanidin can suppress quorum sensing in *Klebsiella pneumoniae*, achieving approximately 72.43% biofilm eradication through the inactivation of LAS signaling receptors (33–36).

Antibiofilm Effects of Plant-Derived Extracts

Plants naturally produce a range of defense compounds—including secondary metabolites and natural pesticides—that protect them from microbial invasion and insect predation. In recent years, these inherent properties have been leveraged for novel pharmacological applications, including preventing biofilm formation. Researches on the antibiofilm activity of plant polyphenols and other compounds have shown promising results for preventing biofilm-associated infections in clinical settings (4). This section focuses on the potential of various plant-derived substances—such as alkaloids, flavonoids, phenols, terpenes, polyphenols, and tannins—to inhibit biofilm formation. For example, berberine, an alkaloid, has been shown to restrict biofilm development by *Staphylococcus epidermidis* by binding to

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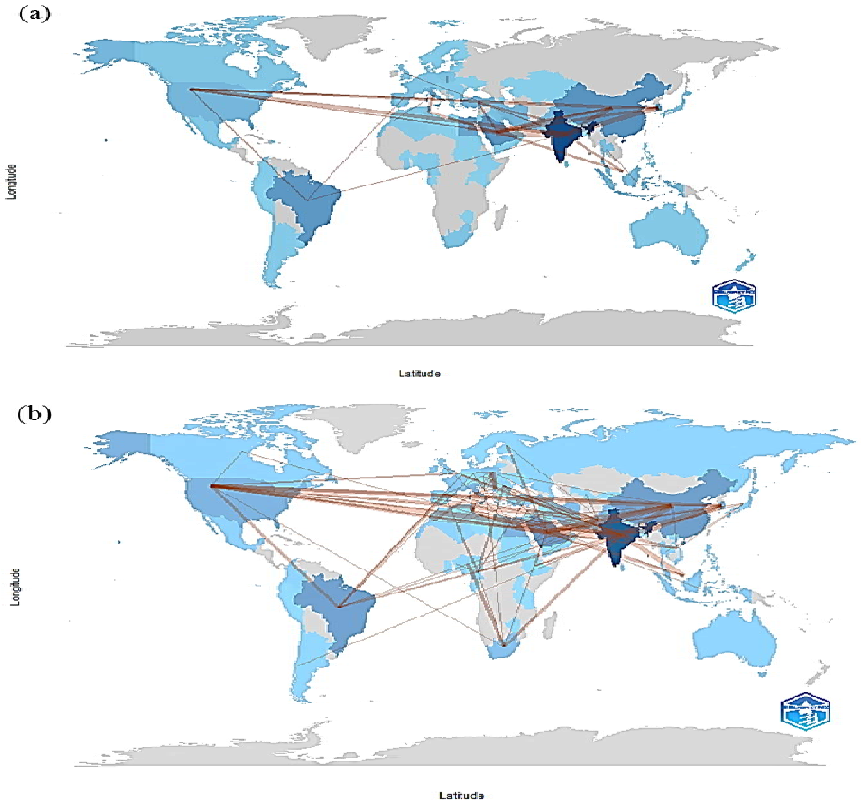

Fig 7: The Collaboration Map by frequency is generated from the bibliometrix R package

amyloid proteins in forming exopolysaccharides (60, 61). Similarly, macrocarpals isolated from *Eucalyptus globulus* leaves exhibit anti-adhesive properties that can mitigate infections caused by multidrug-resistant *Pseudomonas aeruginosa* (62). Research on techtochrysin, derived from the leaves of *Scutellaria oblonga*, demonstrated significant reductions in biofilm formation—73.5% for *S. aureus*, 75.5% for *E. coli*, and 88.9% for *Bacillus subtilis* (40). In addition, pinostrobine, a flavanone naturally present in honey and some plants has shown potent antibiofilm activity against *P. aeruginosa* at concentrations as low as 0.5 µg/ml (63) (Table 2).

Furthermore, experimental studies have revealed that polyphenols extracted from grape pomace, grape seeds, and red wine can inhibit the formation of multispecies biofilms composed of oral bacteria such as *Streptococcus sobrinus*, *Actinomyces viscosus*, *Lactobacillus rhamnosus*, *Fusobacterium nucleatum*, and *Porphyromonas gingivalis*, while also promoting the synthesis of insoluble glucosides (63, 64). In another example, morin—isolated from *Psidium guajava* and *Maclura pomifera* leaf extracts—effectively reduced biofilm development and the virulence of *Listeria monocytogenes*, a major foodborne pathogen (65). These findings suggest that plant-derived antibiofilm agents hold considerable promise for developing natural therapies to manage biofilm-associated infections in medical and industrial settings. Moreover, combining these natural compounds with conventional antimicrobial agents may offer integrated treatment strategies to combat

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Table 2 Antibiofilm performance of different plant sources

Plant species	Common name	Plant part utilized	Potential antibiofilm Constituent	Pathogenic strain	Dosage	Ref.
Allium cepa	Onion	Peel	Quercetin	*Pseudomonas aeruginosa*	1200 µg/ml	(37)
				Aeromonas hydrophila	800 µg/ml	
				Chromobacterium violaceum	500 µg/ml	
Allium cepa	Onion	Peel	Quercetin	*Acinetobacter baumannii*	-	(38)
				Staphylococcus aureus	-	
				Pseudomonas aeruginosa	-	
				Escherichia coli	-	
Allium sativa	Garlic	Clove	Silver nanoparticle	*Pseudomonas aeruginosa*	100 µg/ml	(39)
				Staphylococcus aureus		
Arnebia euchroma	Ratanjot	Root	Silver Nanoparticle	*Staphylococcus aureus*	12- 16 µg/mL	(40)
				Escherichia coli		
				Enterococcus		
				Pseudomonas aeruginosa		
				Salmonella typhi		
				Proteus vulgaris		
				Aspergillus niger		
				Fusarium oxysporum		
				Cuneate fasciculus		
				Candida auris		
				Rhizoctonia		
Azadirachta indica	Neem	Leaf	Azadirachtin	*Streptococcus mutans*	50 µl/ml	(41)
Laurus nobilis	Bay laurel	-	Ergosterol and Sorbitol with essential oil	*Candida albicans*	1000 µg/ml	(42)
Cannabis sativa L.	Hemp	Seed	Caffeoyltyramine and Cannabisin A, B, C	*Staphylococcus aureus*	0.5 mg/ml	(43)

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Cardiospermum halicacabum	Balloon vein	Leaves	Copper nanoparticle	*Pseudomonas aeruginosa* *Escherichia coli* *Staphylococcus aureus*	100 µg/ml	(44)
Cuminum cyminum	Cumin	Cereal	Essential oil	*Vibrio spp.*	50 mg/mL	(45)
Eleusine coracana	Finger millet	Seed	Beta glucan	*Enterococcus faecalis* *Proteus vulgaris* *Lysinibacillus fusiformis* *Shigella sonnei*	100 µg/ml	(46)
Mangifera indica	Mango	Twig	Methyl gallate	*Staphylococcus aureus* *Pseudomonas aeruginosa* *Escherichia coli*	8 mg/ml	(47)
Momordica charantia	Bitter guard	Fruit	Charantadiol A	*Prevotella intermedia* *Porphyromonas gingivalis*	-	(48)
Murraya koenigii	Sweet neem	Leaf	Spathulenol with essential oil	*Pseudomonas aeruginosa*	3% v/v	(49)
Nigella sativa	Black cumin	-	Gold nanoparticle	*Vibrio harveyii* *Staphylococcus aureus*	20-80 µg/ml	(32)
Phyllanthus emblica	Amla	-	-	*Pseudomonas aeruginosa*	6.25 mg/ml	(50)
Phyllanthus emblica	Amla	Fruit	Chromium oxide nanoparticles	*Pseudomonas aeruginosa* *Salmonella enterica* *Proteus vulgaris* *Enterobacter aerogenes* *Acinetobacter baumannii* *Staphylococcus aureus* *Escherichia coli* *Klebsiella pneumoniae*	-	(51)
Psidium guajava	Guava	Leaves	-	*Streptococcus gordonii*	0.78 mg/ml	(52)
Musa acuminate	Dwarf banana	Fruit Peel	5 hydroxymethylfurfural	*Pseudomonas aeruginosa*	400 µg/ml	(53)

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Vitis vinifera	Grape	Seed	-	*Staphylococcus aureus*	25 µg/ml	(54)
				Escherichia coli	250 µg/ml	
Zingiber officinate	Ginger	Rhizome	-	*Chromobacterium violaceum*	-	(55)
				Pseudomonas aeruginosa		
Ziziphus jujuba	Jujube	Leaf	Alphitolic acid	*Streptococcus mutans*	1024 µg/ml	(56)
Carica papaya	Papaya	-	Papain	*Campylobacter jejuni*	5 µg/ml	(57)
Malus domestica	Apple	Pomace	Ursolic acid	*Klebsiella pneumoniae*	0.8 mg/ml	(58)
Moringa oleifera	Drum stick	Seed	Behenic acid with methanolic seed extract	*Staphylococcus aureus*	20 mg/L	(59)

persistent infections and the challenge of antimicrobial resistance.

Antimicrobial Applications of Plant Extracts

Antibiofilm polysaccharides offer a promising alternative for preventing biofilm formation and the infections that arise from microbial overgrowth. These compounds are notable for two reasons: they can effectively block biofilm development without exerting bactericidal effects—thereby minimizing the risk of resistance—and they are widely used as stabilizers and emulsifiers in the food industry. For example, xanthan gum and guar gum (labelled as E415 and E412, respectively) are common additives. Additionally, *Lactobacillus plantarum* KX041, known for its high exopolysaccharide (EPS) production, has emerged as a potential natural substitute for synthetic additives by enhancing surface quality. The produced EPS demonstrates non-Newtonian pseudoplastic behavior and prevents syneresis in various formulations (56, 66–69).

In medicine, considerable research has focused on preventing biofilm formation on human tissues and clinical devices. Recent developments in antibiofilm therapy have incorporated advanced agents into indwelling devices, addressing persistent issues associated with biofilm-related infections (70–73). In dentistry, for instance, biofilms that form on biomaterials used in endodontics, cardiology, and restorative procedures can lead to infections and the degradation of dental hard tissues. Enhancing the antibiofilm properties of these materials represents a promising therapeutic strategy in clinical practice (74–76).

Laboratory studies have demonstrated that blends of medicinal plant extracts—sourced from *Azadirachta indica*, *Cinnamomum zeylanicum*, *Centella asiatica*, *Psidium guajava*, *Mentha spicata*, and *Syzygium aromaticum*—can significantly disrupt biofilm formation by opportunistic pathogens such as *Pseudomonas aeruginosa* in hospital settings. These effects are attributed to bioactive compounds with therapeutic potential. Similarly, extracts from various medicinal and nutritional plants have been shown to inhibit *Listeria monocytogenes*. This gram-positive bacterium forms robust biofilms on human mucosal surfaces and poses serious risks to pregnant women, newborns, and immunocompromised individuals (7). In industrial water systems, biofilm formation by microorganisms can have a major impact on

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operations. Here, innovative antibacterial polymers—including N-acetyl-L-cysteine (NAC)—are employed as effective antibiofilm agents. NAC, in particular, has demonstrated the ability to reduce biofilm formation by *P. aeruginosa*, *Staphylococcus epidermidis*, *Helicobacter pylori*, and *Bacillus cepacia* on both organic and inorganic surfaces (77–80).

Efforts to curb biofilm development extend to marine environments as well. Researchers have investigated the antibiofilm properties of various marine organisms, including seaweeds, bacteria, and sponges, to isolate advanced bioactive metabolites. Certain marine microorganisms have proven to be valuable sources of compounds that interfere with the biochemical processes underlying biofilm formation. For instance, the methanolic extract of the marine brown algae *Halidrys siliquosa* has shown significant efficacy against a range of organisms, including *Staphylococcus*, *Streptococcus*, *Pseudomonas*, *Stenotrophomonas*, *Enterococcus*, and *Chromobacterium*. In addition, fucoidan—a compound extracted from *Fucus vesiculosus*—has been identified as an effective antimicrobial agent against *Streptococcus sobrinus* (81).

Conclusion

Scientific interest in the removal of biofilm has advanced significantly in recent decades. Microbes establish biofilms to safeguard their environment and preserve vital nutrients for life by forming extracellular polymeric networks. Developing microbial colonies inside biofilm matrices in many industrial facilities presents significant infection risks across diverse age demographics. This study provided an overview of biofilm development and the challenges involved with removing the adhesion of sessile microbes to surfaces. Identifying new antibiofilm agents from plant extracts to inhibit biofilms produced by diverse pathogenic bacteria is more advantageous than antibiotic-resistant medications. Ultimately, antibiofilm agents may be formulated utilizing several plant extracts, alone or in combination. Future strategies for using these plant sources in microbial inhibition may offer a viable alternative to preventing microbial biofilm development across many domains.

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