Antibacterial Phytochemicals Identified in Food Wastes

Subjects: Food Science & Technology

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Plants produce a variety of secondary metabolites, making them an area of interest in the search for new phytochemicals to cope with antimicrobial resistance (AMR). A great part of agri-food waste is of plant origin, constituting a promising source of valuable compounds with different bioactivities, including those against antimicrobial resistance. Many types of phytochemicals, such as carotenoids, tocopherols, glucosinolates, and phenolic compounds, are widely present in plant by-products, such as citrus peels, tomato waste, and wine pomace.

agri-food wastes | phytochemicals | multidrug resistance | bacterial infection | antibacterial activity

1. Introduction

Phytochemicals are natural chemical compounds found in plant foods, such as fruits, vegetables, legumes, whole grains, nuts, seeds, and herbs. These compounds act as a natural defence system for plants, protecting them from infections and microbial invasions and giving them colour, aroma, and flavour [1]. Phytochemicals have emerged as safe alternatives to conventional antibiotics to treat antibiotic-resistant pathogen-originated infections, as well as an alternative to chemical additives to foodborne bacteria [2]. Many phytochemicals have demonstrated their potential as bactericidal agents and have proved to inhibit the vital events for the sustenance and resistance of the pathogen, including efflux pumps, replication machinery, and cell permeability, among others [3]. Phytochemicals are grouped according to their structural characteristics into four large groups: nitrogen alkaloids, phenolic compounds, terpenoids, and organosulfur compounds [1].

Agri-food wastes comprise peels, seeds, shells, pomace, and leaves. These residues are important substrates for phytochemicals, including polyphenols, carotenoids, essential oils, tocopherols, and terpenes. In addition to their antibiotic activities, phytochemicals found in agri-food wastes can be easily managed via their valorisation to produce value-added products, food additives, therapeutics, or other environmental applications due to their antioxidant, therapeutic, and nutritional properties [4][5][6][7] (**Figure 1**).

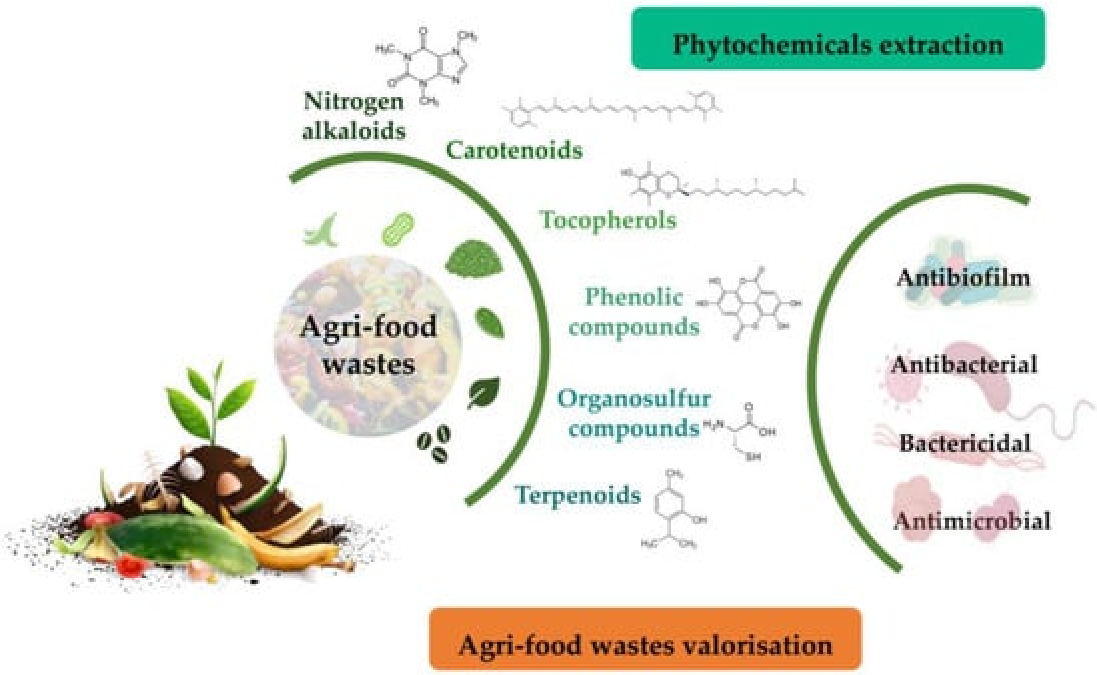
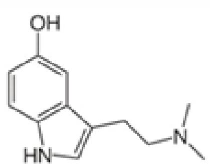
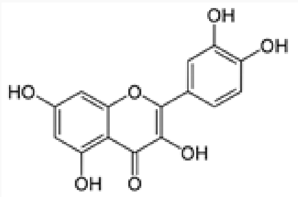


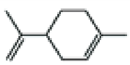
Figure 1. Overall strategy to unveil phytochemicals with antimicrobial activity from food wastes as a strategy for their valorisation.

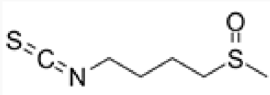
Several studies have shown the antibacterial potential of phytochemicals found in agri-food wastes (**Table 1**). For instance, Carmo and collaborators [8] isolated coumarins (bergapten, xanthotoxin, dimethyl allyl xanthyletin) and an imidazole alkaloid from the crude extract of leaves and bark of *Pilocarpus pennatifolius* Lemaire. The extracts and pure compounds were tested against different strains of bacteria and fungi, which showed promising antimicrobial and antifungal activities. The alkaloid identified showed a minimal inhibitory concentration of 1.56 μg·mL^{-1} against *Enterococcus fecalis*, and 1.56 μg·mL^{-1} and 6.25 μg·mL^{-1} against *Salmonella enteritidis* and *Pseudomonas aeruginosa*, respectively. The extracts of the studied species proved to be an alternative source in the search for new antimicrobial agents for the treatment of diseases caused by bacteria.

Table 1. Antibacterial potential of phytochemicals found in agri-food wastes.

Phytochemicals	Agri-Food Waste	Target Pathogen	Action	Ref.
 Nitrogen alkaloids				
Imidazole	*Pilocarpus pennatifolius* (jaborandi) leaves	Gram-positive (*Enterococcus fecalis)* and Gram-negative	Antibacterial	[8]

Phytochemicals	Agri-Food Waste	Target Pathogen	Action	Ref.
		(*Salmonella enteritidis*, *P. aeruginosa*)		
Trigonelline, caffeine	Arabica coffee leaves	Gram-positive (*S. aureus*) and Gram-negative (*E. coli*, *P. aeruginosa*)	Antibacterial and bactericidal	[9]
Caffeine, quinine	Coffee silverskin extracts	Gram-positive (*S. aureus*) and Gram-negative (*E. coli*, *P. aeruginosa*)	Antibiofilm	[10]
Peganine, harmol, harmine, β-carboline, quinazoline alkaloids	*Peganum harmala* seeds	*Ralstonia solanacearum* Phylotype II, *Pectobacterium cartovorum* subsp. *Cartovorum, Erwinia amylovora, Burkholderia gladioli* pv. *allicola*	Antibacterial	[11]
Solanidine, α-chaconine, α-solanine	Potato peels	*Lactobacillus reuteri*, *Lactobacillus acidophilus*, *Lactobacillus rhamnosus*, *E. coli*	Antimicrobial	[12]
α-Solanine, α-chaconine	Potato sprouts	Gram-positive bacteria (*S. aureus*, *Bacillus subtilis*, *Enterococcus hirae*) and Gram-negative (*E. coli*, *P. aeruginosa*)	Antimicrobial	[13]
 Phenolic compounds				
Ellagic acid, trans-fertaric acid, quercetin, kaempferol	Grape pomace and lees	Gram-positive (*S. aureus*, *Bacillus subtilis*, *Bacillus cereus*) and Gram-negative (*E. coli*)	Bactericidal	[14]
Quercetin and its glucosides (quercetin aglycone, quercetin-4′-*O*-	Skinned onions	Gram-positive (*S. aureus*, *Bacillus cereus*)	Antibacterial and antibiofilm	[15]

Phytochemicals	Agri-Food Waste	Target Pathogen	Action	Ref.
monoglucoside, quercetin-3,4′-*O*-diglucoside, anthocyanin)		and Gram-negative (*E. coli*, *P. aeruginosa*)		
Sinensetin, 4′,5,6,7-tetramethoxyflavone, nobiletin, tangeretin, 3,3′,4′,5,6,7-hexamethoxyflavone, 3,3′,4′,5,6,7,8-heptamethoxyflavone, eriocitrin, nairutin, hesperidin	Orange peels	*E. coli*, *S. aureus*, *Bacillus subtilis*	Antibacterial	[16]
Hesperidin, eriocitrin, diosmin	Lemon peels	*S. aureus*	Antibacterial	[17]
Pelargonidin-diglucoside, gallotannin, ellagitannin, cyanidin-glucoside, pelargonidin-glucoside, catechin, p-coumaroyl-glucoside, *p*-coumaroyl-ester, *p*-coumaroyl-glucoside, quercetin-rutinoside, ellagic acid, quercetin-glucoside, quercetin-glucuronide, methyl-ellagic acid-pentose, and kaempferol-glucuronide.	*Camellia oleifera* seeds	*E. coli*, *S. aureus*, *Bacillus subtilis*	Antibacterial	[18]
Chlorogenic acid, caffeic acid, coumaric acid	Apple, lime, grapes, pomegranate, and papaya wastes	*Bacillus subtilis*, *E. coli*	Antibacterial activity of pigments	[19]
 Terpenoids				
Limonene, linalyl acetate, linalool, β-pinene, γ-terpinene	Citrus peels (orange, lemon, and bergamot)	*S. aureus*	Bactericidal	[20]
Limonene, β-myrcene, linalool, α-pinene, β-pinene	Orange peels	Gram-positive (*S. aureus*, *Listeria monocytogenes*) and Gram-negative (*E. coli*, *P. aeruginosa*)	Bactericidal	[21]
Caffeic acid, *p*-coumaric acid, salicylic acid	Yellow passion fruit pulp and seeds	Gram-positive (*S. aureus*, *Bacillus cereus*) and Gram-negative (*E. coli*, *Salmonella enteritidis*)	Antibacterial	[22]
D-limonene, lauric acid, 1-methyl-1,4-cyclohexadiene, methyl linoleate,	Orange peels	*Cutibacterium acnes* (formerly	Antibacterial	[23]

Phytochemicals	Agri-Food Waste	Target Pathogen	Action	Ref.
myristic acid, (E,E,E)-2,6,10-trimethyl-2,6,9,11-dodecanetetraen-1-al, palmitic acid, β-myrcene		*Propionibacterium acnes*)		
 Organosulfur compounds				
Glucoraphanin, sulforaphane, sulforaphane nitrile	[1] *Punica granatum* L. peel	Gram-positive (*S. aureus*, *Enterococcus faecalis*) and Gram-negative (*P. aeruginosa*, *Klebsiella pneumoniae*)	Antibacterial	[24]
[1][3] Allyl isothiocyanate [9][10]	*Lepidium latifolium* flower, leaf, stem, and root	Gram-positive (*Listeria monocytogenes*, *S. aureus*) and Gram-negative (*Salmonella* Typhimurium, *E. coli*, *P. aeruginosa*)	Antibacterial a (time-killing and growth kinetic assays)	[25]
Lucoraphanin, sulforaphane, sulforaphane nitrile	Broccoli (raw, [9] cooked, and cooked broccoli plus mustard seeds as a source of myrosinase)	*E. coli*	Antibacterial	[26]

antibiotics beneficial structures ell-known mpounds *fortuitum*, *Klebsiella* bioactive d that the t *E. coli*. ne phenol group and have an aromatic ring with one or more hydroxyl groups in their molecular structure [2], and they are classified into flavonoids and non-flavonoids based on their structural characteristics [1][3] secondary metabolites that play a crucial role in plant physiology, including defence against herbivores and pathogens and mechanical support for the plant. [1] have shown antimicrobial properties against a wide range of microorganisms, and they can sensitize multidrug-resistant strains to bacteriostatic or bactericidal antibiotics, making them promising natural antimicrobial agents [3]. Additionally, polyphenols have been established as chemopreventive and therapeutic agents due to their potential health-benefiting properties, including antioxidant, antiallergic, anti-inflammatory, anticancer, antihypertensive, and antimicrobial features [1][2][3]. Sharma et al. [15] investigated the biological activities of polyphenols in skinned fresh and ageing onions. The authors found that the antibiofilm activity against *E. coli*, *P. aeruginosa*, *S. aureus*, and *Bacillus cereus* increased with ageing onions as the levels of quercetin and total phenolic content also increased upon aging in the studied varieties.

3.1. Flavonoids

Plant flavonoids, which have a 2-phenyl-benzo-γ-pyrane nucleus with two benzene rings, have demonstrated promising antimicrobial activities and antioxidant properties [1][3]. Many classes of flavonoids, including flavonols, flavanols, flavanones, isoflavonoids, chalcones, and dihydrochalcones, have been identified as allelochemicals that inhibit microbial growth. Flavonoids are also known to inhibit quorum sensing and biofilm formation, as well as act as resistant-reversal agents [3]. Catechins and proanthocyanidins possess antioxidant properties and have been proposed to neutralize bacterial toxic factors originating from *V. cholerae*, *V. vulnificus*, *S. aureus*, *Bacillus anthracis*, and *C. botulinum*. Additionally, citrus flavonoids, such as apigenin, kaempferol, quercetin, and naringenin, are effective antagonists of cell–cell signalling [2][27]. Chrysin and kaempferol restrict the DNA gyrase activity, which is an essential enzyme in DNA replication in *E. coli*, while aglycone flavonoids, such as myricetin, hesperetin, and phloretin, inhibit biofilm formation in *Staphylococcus* strains [3].

3.2. Non-Flavonoids

Phenolic acids, including benzoic, phenylacetic, and phenylpropionic acids, have been discovered to have inhibitory effects on both pathogenic and non-pathogenic bacteria and fungi. These include *E. coli*, *Lactobacillus* spp., *S. aureus*, *P. aeruginosa*, and *Candida albicans* [2][3].

Hydroxycinnamic acids, such as caffeic, coumaric, ferulic, and sinapic acids, have also been found to inhibit the growth of *Bacillus cereus*, *S. aureus*, and *Pseudomonas fluorescens* [2]. Ferulic acid and gallic acid have also demonstrated antibacterial properties against various bacterial isolates. Both acids damage the cell walls of *E. coli*, *P. aeruginosa*, and *S. aureus*, leading to local damage and cellular material leakage [3]; gallic acid has been shown to exhibit strong antibacterial potential against *Enterococcus faecalis*, *Streptococcus pneumonia*, *P. aeruginosa*, *Moraxella catarrhalis*, *S. aureus*, *Enterococcus faecalis*, *E. coli*, and *Streptococcus agalactiae* strains [3].

4. Terpenoids

Terpenoids are a diverse group of organic compounds that are similar to terpenes. They consist of mono- and sesquiterpenoids [1], which are the main components of essential oils. Essential oils are volatile plant products [3] that can be extracted from various plant parts, such as flowers and fruits. They contain a mixture of low-mass plant natural products or phytochemicals, including myrcene, *o*-cimene, citral, geraniol, eugenol, carvacrol, linalool, citronellal, carvone, limonene, terpinenes, menthol, and menthone [1][3].

Essential oils have strong antimicrobial properties and are commonly used in traditional medicine. They are considered safe for consumption and vital host tissues. However, their stability is crucial for their quality and pharmacological potency [3]. Essential oils are known for their remarkable antibacterial activities against both Gram-positive and negative pathogens, including bactericidal and re-potentiating or re-sensitizing of antibiotics potentials against pathogenic microbes. They have also demonstrated their potential in targeting and disturbing the most prevalent drug-resistance-determining mechanisms of microbes, namely the cell wall, cell membrane and permeability, drug efflux pumps, mobile genetic elements, quorum sensing, and biofilm [3].

Citrus fruits are the main source of essential oils [1][20][21][23]. For example, Djenane [20] evaluated the chemical composition of citrus peel (orange, lemon, and bergamot) essential oils. The essential oils analysed were mainly composed of limonene (77.4%) for orange essential oil; linalyl acetate (37.3%) and linalool (23.4%) for bergamot essential oil; and limonene (51.4%), β-pinene (17.0%), and γ-terpinene (13.5%) for lemon essential oil. The in vitro antimicrobial activity of the essential oils was evaluated against *S. aureus*, which revealed that lemon essential oil had more antibacterial effects than the other essential oils.

5. Organosulfur Compounds

Organosulfur compounds, also known as thiols, are present in various plants and vegetables. These compounds include glucosinolates and allyl sulphides, which contain sulfur in their structure. Glucosinolates are found in cruciferous vegetables of the *Brassicales* order while allyl sulphides are abundant in garlic [1].

Glucosinolates play a vital role in plant defence against microbial pathogens and insect herbivores. They act as signalling molecules that initiate pathways such as stomatal closure, apoptosis, and callose accumulation [28]. A study by Blažević et al. [25] investigated the glucosinolate profile and antibacterial activity of *Lepidium latifolium* L. against food spoilage bacteria. The results showed that allyl isothiocyanate, a compound found in the plant, was highly effective against *E. coli*.

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