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Review Article

Recent Advances in Antimicrobial and Antioxidant Food Additives Obtained From Agrifood Waste: A Review

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Consumers' preference on the food market has shifted from food safeguarded with artificial preservatives to that safeguarded with antimicrobial and antioxidant preservatives derived from natural sources. This is why there is a growing interest among researchers in the food and beverage industry to explore natural antimicrobial and antioxidant preservatives as an alternative to artificial preservatives. The present investigation is, therefore, aimed at synthesising the current outcomes that have achieved success in safeguarding spoilage and growth of spoilage microbes on foodstuffs. The present study used a literature review–based approach in which peer-reviewed published papers on 'antimicrobials and antioxidants from agri-food wastes' were accessed from ScienceDirect, PubMed, Google Scholar, PLOS, SciFinder and Web of Science databases. The findings from the papers on the antimicrobial and antioxidant activities of different agrifood wastes such as *Citrus limon* peel, *Allium cepa* peel, *Malus domestica* seeds, *Daucus carota* peels, *Beta vulgaris* peel, citrus fruit peel, *Musa acuminate* peels and *Vitis vinifera* waste extracts on meat, milk and baked products were systematically reviewed. The literature revealed that natural antioxidants resulted in a reduction in the oxidative processes in tested meat, milk and baked products. Similarly, the natural antimicrobials resulted in inhibition of the spoilage microbe growth, thereby extending the shelf life of various foods. The antioxidant and antimicrobial activities of the agrifood waste extracts were attributed to the existence of phytochemical compounds such as phenolic acids, gallic acid, vanillic acid and flavonols. The literature has shown that bioactive compounds in agrifood waste are suitable natural antimicrobials and antioxidants and demonstrated the increase in the shelf life of food products.

Keywords: agrifood waste extracts; extraction techniques; natural antimicrobials; natural antioxidants; phytochemical compounds

1. Introduction

Food additives are chemical substances added to food during processing and packaging to promote its organoleptic properties but are never consumed as food on their own [1]. They are categorised into two types: synthetic and natural. However, food additives are classified according to their functions, namely nutritive agents (vitamins, minerals and bioelements), processing agents (emulsifiers, stabilisers, thickeners, foaming and anticaking), sensory agents (colorants, sweeteners and flavour enhancers) and preservative agents (antimicrobials and antioxidants), as shown in Figure 1 [2]. The presence of additives in processed foods is reported to serve various functions such as promoting desired food characteristics, for instance, improving flavour, preserving freshness or texture and increasing shelf life [3, 4]. Apart from promoting food characteristics, food additives such as colourings, flavours and preservatives are used to enhance taste and appearance, prevent microbial growth, reduce oxidation and increase product stability [5, 6]. Most of the food processors use synthetic additives in processing food products as they have proved to be effective,

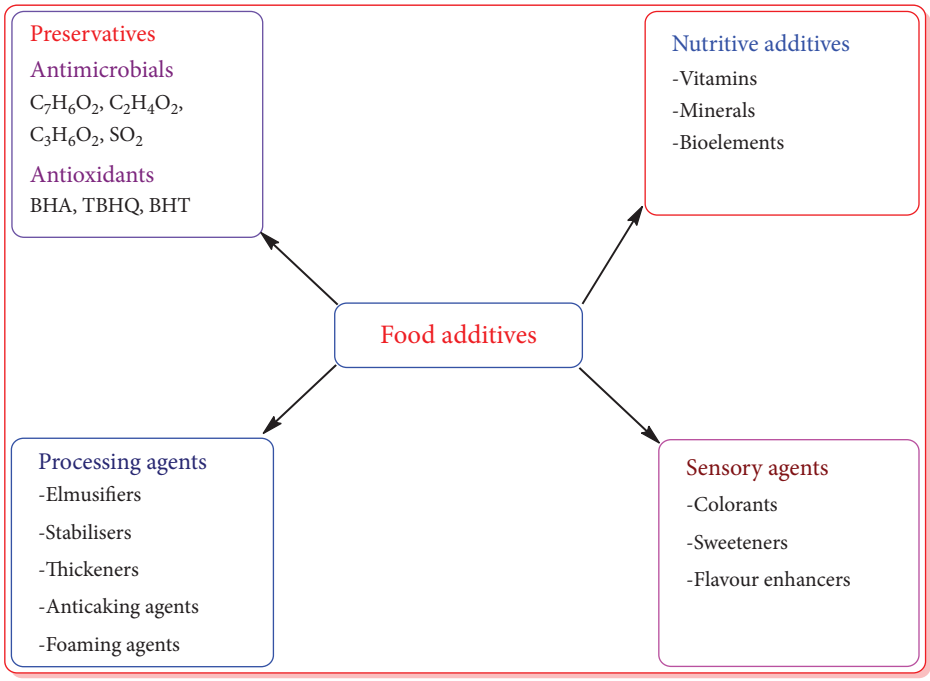


Figure 1: Classification of food additives according to their functions.

affordable and readily available [7]. The synthetic food additives are prepared in modern and advanced chemical laboratories through a chain of chemical reactions. However, consumers' choice has recently shifted towards natural additives as they are less hazardous, healthier and contain significant bioactive compounds that provide health benefits compared to synthetic additives [8].

The United Nations Sustainable Goals target to reduce food waste by half by 2030 [9]. However, the quantities of food waste produced in the agrifood chain sector continue to increase worrisomely worldwide [10]. Globally, 5 billion metric tonnes of agrifood wastes are produced every year, thereby creating disposal challenges [11]. In sub-Saharan African countries, food wastage occurs in large volumes with perishable commodities such as fruits and vegetables as the major culprits [10]. This significant loss threatens food security as foods are essential for human well-being due to economic growth and diet expansion [10]. Studies have shown that raw and underutilised agrifood wastes, which are rich reserves of phytochemical compounds, are commonly disposed of through burning, dumping and burying in landfills [12, 13]. These methods of disposal are associated with environmental issues such as the release of harmful substances (nitrogen compounds, salts, pathogens and certain toxic metals) into the soil and water and emission of greenhouse gases (GHGs) into the atmosphere [12, 13].

Recent research studies have detected synthetic food additive nanomaterials (NMs) in the environment, such as aquatic, edible leaves and soil matrices [14]. The NMs are reported to be resistant to conventional wastewater treatment plants and end up in the environment, such as in water resources. NMs are hazardous to soil, marine and terrestrial life and can be transferred to the human body through the consumption of plants and animals among other sources [15].

Internationally, there has been an increased interest in exploring the antioxidants and antimicrobial food preservatives sourced from natural origins, such as agrifood wastes, microorganisms and animals, as a viable alternative to replace synthetic food additives due to safety issues [16, 17]. Studies have indicated that incorporation of synthetic food additives, for instance, SiO_2, TiO_2, metallic silver and gold, in processed food products is associated with serious health effects [18]. The human health challenges, for example, allergies, cancer, hyperactivity, respiratory infections and disturbance of the gut microbiota that is common in children, have been associated with the excessive consumption of synthetic additives [19]. The natural additives are reported to consist of remarkable bioactive properties that help to overcome oxidative stress and promote human health benefits [20].

Phytochemical compounds present in different sources of agrifood wastes, such as peels, seeds, leaves, barks and other plant parts, as shown in (Table 1), are obtained through the use of various extraction methods [21].

The extraction process depends on several factors such as solvent or matrix properties, particle size, process pressure and extraction technique [34]. In general, the process of attaining and isolating phytochemical compounds from agrifood wastes follows several stages as shown in Figure 2. However, the extraction process is regarded as the most significant stage. The extraction of phytochemical compounds, such as phenolic acids, requires the use of solvents, for example, methanol, ethanol and acetone [35, 36]. Each

Table 1: The phytochemical compounds found in agrifood waste.

SN	Agrifood waste	Phytochemical bioactive compounds	References
1.	*Malus pumila* peel	Epicatechin, catechins, anthocyanins, chlorogenic acid, hydroxycinnamates, procyanidins	[22, 23]
2.	*Musa acuminata* peel	Gallocatechin, anthocyanins, delphinidin, cyanidin, catecholamine	[24]
3.	*Litchi chinensis* pericarp and seeds	Cyanidin 3-glucoside, cyanidin 3-rutinoside, malvidin 3-glucoside, gallic acid, epicatechin 3-gallate	[25, 26]
4.	Citrus fruit peel	Hesperidin, naringin, eriocitrin, narirutin	[27]
5.	*Persea americana* peel and seeds	Epicatechin, catechin, gallic acid, chlorogenic acid, cyanidin 3-glucoside	[28]
6.	*Mangifera indica* kernel	Gallic acid, ellagic acid, gallates, gallotannins, condensed tannins	[29, 30]
7.	*Psidium guajava* skin and seeds	Catechin, cyanidin 3-glucoside, galangin, gallic acid, homogentisic acid, kaempferol	[28]
8.	*Solanum lycopersicum* skin	Carotenoids	[31]
9.	*Cucumis sativus* peel	Chlorophyll, pheophytin, phellandrene, caryophyllene	[32]
10.	*Daucus carota* peel	Phenols, beta-carotene	[33]

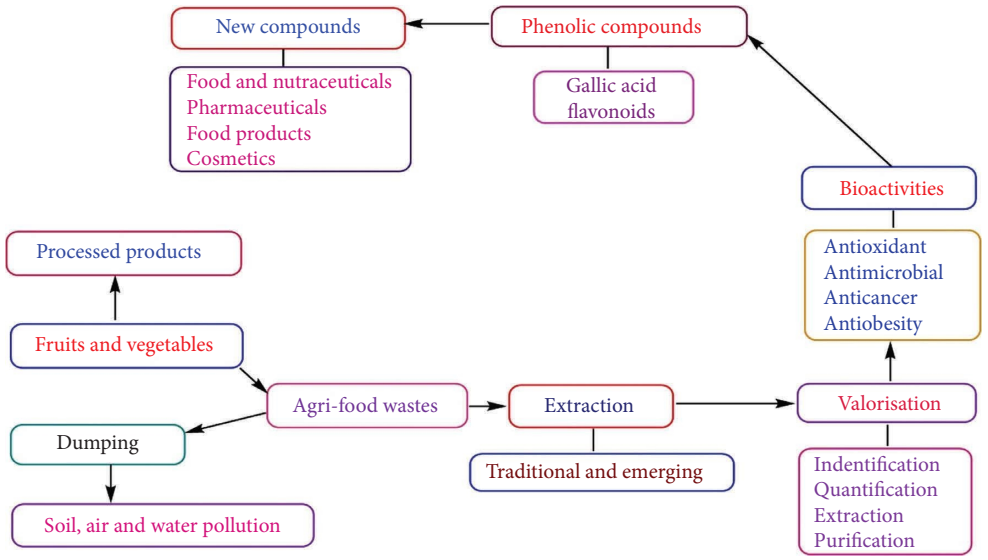


Figure 2: Extraction and isolation of phytochemical compounds from agrifood waste.

extraction method has specific bioactive compounds that can be recovered from the agrifood waste and also existing advantages and disadvantages [37]. The extraction protocols are grouped into traditional and emerging [38].

Traditional extraction techniques for obtaining bioactive compounds from agrifood sources generally require the use of solvents depending on polarity requirements. Solvents such as water and alcohol are commonly used for the extraction of polar compounds, whereas nonpolar compounds are obtained through the use of nonpolar solvents such as hexane, chloroform and ether [39]. The traditional extraction methods require the use of heat and continuous agitation. Examples of this type of technique are Soxhlet, maceration and hydrodistillation [40, 41]. Recent studies have explored several environmentally friendly extraction technologies as viable options to traditional methods. Microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), subcritical water extraction (SWE), assisted negative pressure cavitation and ultrasound-assisted extraction (UAE) have been developed to overcome the setbacks associated with the traditional extraction protocols [42, 43]. Amongst emerging extraction methods, the MAE method is the most favoured owing to its short extraction duration and requires less volume of solvent [42, 44]. Furthermore, UAE and solid-state fermentation and emerging methods of extraction have gained recognition for the excellent outcomes of obtaining gallic acid, quercetin, carotenoids, polyphenol, hesperidin, hesperetin, terpenoids, antioxidant and antimicrobial compounds from different sources of agrifood waste [11, 45–48].

Therefore, this study is aimed at exploring and analysing published peer-reviewed papers regarding recent advances towards the potential use of natural preservatives obtained from agrifood waste as antimicrobials and antioxidants to enhance food safety and shelf life. The agrifood waste materials are reported to possess high levels of phytochemical substances, which are vital for human health and overcoming environmental and health toxicities associated with the consumption of synthetic chemicals. Additionally, the study is aimed at adding value to agrifood waste owing to the substantial disposal challenges, thereby promoting global food security and sustainability efforts [49].

2. Methodology

2.1. Search Strategy. The present study adopted a literature-based survey approach that involved accessing and downloading several published peer-reviewed papers in line with this topic of study. The papers were selected from databases based on their relevance to the study topic and recency in publication. The articles published from 2007 to 2024 were prioritised. The papers were obtained from different scientific database sites (Google Scholar, PubMed, ScienceDirect, SciFinder, PLOS and Web of Science). The keywords "Natural Additives", "Antimicrobials", "Antioxidants", "Synthetic additives" and "Food preservatives" were among the searched words.

2.2. Inclusion and Exclusion Criteria. This review included studies that met these criteria: (i) examined the effectiveness of agrifood waste as a food preservative, (ii) discussed different ways of extracting useful compounds from agrifood waste and (iii) were peer-reviewed articles from respected journals. The studies that were not reported in languages other than English, the reviews and studies without primary data were excluded from the study.

2.3. Data Extraction and Quality Assessment. The data on agrifood waste, bioactive compounds, extraction techniques, food additives, antimicrobials, antioxidants and challenges associated with agrifood waste were acquired. A total of 275 papers were downloaded, critically scrutinised and analysed by authors through round table discussions to remove duplicates. Finally, a total of 239 remaining papers were used in this review.

3. Results and Discussions

3.1. Extraction of Bioactive. Bioactive compounds are obtained from agrifood wastes following application of several techniques, with extraction being the critical step [50]. Extraction techniques are mainly categorised into traditional and emerging. Traditional technique comprises methods such as solid–liquid and liquid–liquid extraction. However, these protocols are now being substituted with more reliable and green sustainable emerging methods [36]. The emerging extraction techniques consist of supercritical extraction fluid, enzyme-assisted extraction, SFE, pulse electric–assisted extraction and UAE. These emerging extraction techniques are associated with several benefits, which include less energy and solvent usage, environmental friendliness, less waste generation and improved extract quality and quantity [51, 52].

Optimisation of extraction of bioactive compounds from agrifood waste is significant for obtaining higher yields and maximum resource recovery. Studies have reported successful use of emerging extraction techniques at different extraction operating conditions as presented in Table 2. Published reports indicated that various bioactive compounds such as flavonoids, polyphenols, carotenoids and essential oils (EOs) have been successfully recovered under optimised conditions [50]. By employing optimisation studies, extraction protocols promote environmental conservation and value addition to food waste and offer cheap sources of valuable bioactive compounds for various industrial uses [53, 54].

3.2. Importance of Antioxidants. Foods rich in antioxidant compounds such as vegetables and fruits are documented to provide several human health benefits, such as decreasing the risks of chronic diseases, supporting healthy ageing processes and aiding normal brain function. Research studies indicate that anthocyanin compounds demonstrate antiproliferative properties against colon adenocarcinoma cells due to the presence of excellent antioxidant properties [81]. Another study has shown that ginger extracts contain high concentrations of gingerol compounds, which are well documented in the management of chronic infections [82]. Spices and herbs are desired amongst consumers due to the presence of strong antioxidant compounds that are recognised for their human health-promoting properties, rendering them important components for a balanced diet. Furthermore, studies have shown that antioxidants of natural origin are much more tolerated in the human body compared with synthetic additives, which pose serious health threats [83]. Moreover, antioxidants are also attributed to positively promote cognitive functions. Studies conducted on aged individuals have shown that berries rich in antioxidants significantly improved gut health and cognitive functions, an indication that antioxidants can be used in the management of age-related cognitive capacity decrease [84, 85]. Natural antioxidants are also preferred by consumers as they are documented to maintain the nutritional quality and flavours of the stored food products [86, 87]. Other studies have also reported that antioxidants are capable of combating oxidative stress–induced diseases [88, 89]. Consumption of grapes and foods rich with a high content of phenolic acids and flavonoids possesses anti-inflammatory and anticancer properties [90, 91]. Moreover, polyphenols are attributed to providing healthy heart conditions [92]. Studies have recently shown that the synthetic NMs have been detected in the environment due to their nonbiodegradable nature causing pollution. This is in contrast to antioxidants derived from agrifood waste that are known to promote sustainable waste management and the nutritional profile of the preserved foods as they contain high levels of phytochemicals [93, 94].

3.3. Antioxidant Mechanisms. Lipid oxidation and peroxidation are important complex biochemical processes that comprise the degradation of lipids, thereby affecting the overall sensory quality and nutritional value of food products and introducing health concerns [95]. Lipid autoxidation is a chemical reaction involving unsaturated fatty acids with reactive oxygen species (ROS), resulting in the formation of radical compounds through oxidative processes [96]. These radical compounds are further changed into peroxide radicals, which are then converted to aldehydes, ketones and hydroperoxides, thereby preventing

Table 2: Bioactive compounds obtained from agrifood wastes at various extraction parameters through different protocols.

Extraction protocol	Agrifood waste	Extraction conditions	Polyphenols obtained	References
Microwave-assisted extraction (MAE)	*Ananas comosus* waste	Solid-to-liquid ratio (S/L) 30 g/L, 15 min, 300 W	TPC 12.4 mg GAE/g	[55]
	Opuntia joconostle	S/L 100 g/L, H_2O, 5.5 min, 297 W TFC, 5.6 mg CE/g	TPC 12.9 mg GAE/g	[56]
	Sterculia nobilis	S/L 30 g/L, 41% ethanol, 37 min, 67 C, 700 W	TPC 3.7 mg GAE/g TFC 0.45 mg quercetin equivalents (QE)/g	[57]
	Selenicereus undatus fruit peel	S/L 24 g/L, H_2O, 45°C, 20 min, 400 W	TPC 58 mg GAE/g	[58]
	Camellia oleifera meal	S/L 100 g/L, 80% ethanol, 15 min.	TFC 12.8 mg RE/g	[59]
	Brassica oleracea outer leaves	S/L 100 g/L, ethanol, 5 min, 100 W	TPC 14.9–19.2 mg GAE/g	[60]
	Euterpe edulis waste	S/L 20 g/L, 94% ethanol, 100 s, 670 W	TPC 3.8 mg GAE/g TFC 1.6 mg QE/g	[61]
	Prunus armeniaca L. kernel	S/L 25 g/L, 43% ethanol, 80°C, 20 min, 400 W	TPC 22 mg GAE/g	[62]
	Musa acuminata peel	S/L 28.5 g/L, H_2O:ethanol 1:1 v/v, 100 s, 380 W	2.2% polyphenols	[63]
Ultrasound-assisted extraction (UAE)	*Lactuca sativa* leaves	S/L 20 g/L, 50%–75% ethanol, 120 S, 400 W, 24 kHz	81 μg polyphenols	[64]
	Malpighia emarginata residues	S/L 115 g/L, 46% ethanol, 49 min, 50 kHz, 250 W	TPC 10.7 mg GAE/g TFC 5.6 mg QE/g	[65]
	Euryale ferox leaves	S/L 37 g/L, 62% ethanol, 40°C, 38 min	TAC 2.8 mg/g	[66]
	Ginkgo biloba leaves	S/L 100 g/L, phosphate buffer + 68% ethanol, 8.4 mg cellulose, 40°C, 20 min, 218 W	25.4% flavonoids 12.4% ginkgolides	[67]
	Pueraria lobata Ohwi roots	S/L 50 g/L, H_2O/ethanol, 2:8 v//v 80°C, 6 h	7.3 g isoflavones/100 g sample	[68]
	Aronia melanocarpa wastes	S/L 25 g/L, 0%–50% ethanol, 20°C–70°C, 240 min, 0–100 W	TPC > 70 mg GAE/g	[69]
	Ziziphus mauritiana L.	S/L 10 g/L, 60% methanol, 30 min	TPC 12.8 mg GAE/g	[70]
	Brassica juncea seed meal	S/L 25 g/L, 70% ethanol, 40°C, 30 min, 60 W	TPC 13.8 mg sinapic acid equivalents/g	[71]
	Brassica oleracea waste	S/L 50 g/L, 60% methanol, 37°C, 30 min, 40 kHz		[72]
	Zea mays cob	S/L 100 g/L, 20 min, 100 W, ethanol/H_2O/lactic acid 80:19:1	TPC 44–47 mg GAE/g	[73]
	Juglans regia husks	Solid-to-liquid ratio (S/L) 50 g/L, 60% ethanol 60°C, 30 min	TPC 6.9 mg GAE/g	[74]
	Brassica oleracea waste	S/L 50 g/L, 2 M NaOH, 60°C, 15 min, 37 kHz, 180 W	TPC 7.3 mg GAE/g	[75]
Supercritical fluid extraction (SFE)	*Vaccinium myrtillus* waste	Flow rate 0.5 kg/h 5% ethanol + 5% H_2O as cosolvents, 20 MPa, 40°C	TPC 134 mg GAE/g	[76]
Deep eutectic solvent (DES) extraction	*Ginkgo biloba* leaves	S/L 95 g/L, ChCl/malonic acid 1:2 mol/mol, 55% H_2O, 65°C, 53 min	22.2 mg proanthocyanidins/g	[77]
	Mangifera indica waste	S/L 17 g/L, lactic acid/sodium acetate/H_2O, 3:1:4 mol/mol 20 min, 436 W	56.2 mg GAE/g	[78]
	Ruta graveolens leaves	S/L 50 g/L, ChCl/citric acid 2:1 mol/mol + 20% H_2O, 30°C, 90 min	38.2 mg GAE/g	[79]
	Arachis hypogaea roots	S/L 33 g/L, ChCl/1,4-butanediol 1:3 mol/mol + 40% H_2O, 55°C, 40 min of sample	38.9 mg of resveratrol/kg	[77]
Microwave hydrodiffusion and gravity (MHG)	Broccoli waste	43 min, 500 W, atm	317 μg GAE/mL	[80]

potentially detrimental final products [97]. Lipid autooxidation follows three critical stages, namely initiation, propagation and termination, as indicated in Figure 3. The initiation step involves the formation of lipid radicals. This step is accelerated in the presence of transitional metals such as Fe^{2+} ions [98]. Conversely, the propagation step is characterised by a continuation in the formation of peroxyl radicals, which react with unsaturated lipids, resulting in the creation of a sustained chain reaction [95]. This continued process causes serious cellular destruction, specifically by affecting membrane integrity and functions. The terminal stage deals with the transformation of radical species into nonradical products through enzymatic and nonenzymatic activities [96]. This suggests the use of effective methods of safeguarding food products to maintain food quality and safety.

Antioxidant compounds obtained from natural sources are categorised into primary and secondary metabolites. These compounds play a significant role in preventing lipid peroxidation. On one hand, the primary antioxidants are recognised to delay or prevent the initiation stage or interfere with the propagation stage by degrading the compounds [99]. On the other hand, the secondary metabolites increase the efficacy of primary antioxidants through several mechanisms, including the provision of H to primary metabolites, acting as oxygen scavengers, decomposing hydroperoxides to nonradical compounds and chelating metal ions [100]. Synthetic food additive preservatives used in lipid oxidation are butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT). These additives are associated with serious health concerns and are currently being replaced with antioxidants obtained from natural sources [101]. The antioxidants derived from agrifood wastes, especially those possessing a phenolic structure, are capable of donating electrons. Furthermore, these antioxidants arrest free radicals, resulting in the prevention of production of destructive hydroperoxides [102]. Moreover, these antioxidants are capable of competing with free radicals, preventing the propagation of oxidative reactions. They are also able to neutralise the free radicals, thereby making them excellent substances for promoting human health [102].

Studies have shown that the occurrence of polyphenols in agrifood waste extracts is linked to the scavenging of free radicals and enhancement of the formation of ROS, which are responsible for causing bacterial cell destruction resulting in death [103, 104]. The excellent antioxidant and antimicrobial properties of EOs obtained from some herbs have been connected to the presence of polyphenols, increasing their success as natural preservatives [105].

Foods rich in antioxidant compounds such as vegetables and fruits are documented to provide human health benefits. Research studies indicate that anthocyanin compounds demonstrate antiproliferative properties against colon adenocarcinoma cells due to the presence of excellent antioxidants [81]. Another study has indicated that ginger extracts contain high concentrations of gingerols, which are recognised in the management of chronic infections [82]. Similarly, spices and herbs are desired amongst consumers due to the presence of strong antioxidant compounds recognised for their human health-promoting properties, rendering them important components for a balanced diet. Studies have also indicated that antioxidants of natural origin are much more tolerated in the human body compared with synthetic additives, which pose serious health threats [83]. Moreover, antioxidants are also indicated to positively promote cognitive functions. The study conducted on aged individuals had indicated that berries rich in antioxidants have significantly improved gut health and cognitive functions, an indication that antioxidants can be used in the management of age-related cognitive capacity decrease [84, 85]. Antioxidants are also much preferred as they are documented to maintain nutritional quality and flavours of the stored food products, thereby gaining much preference among consumers [86, 87]. Other studies have also reported that antioxidants are capable of combating oxidative stress-induced diseases [88, 89]. Consumption of grapes and foods rich with a high content of phenolic acids and flavonoids, which possess anti-inflammatory and anticancer properties, has several health benefits [90, 91]. Moreover, polyphenols are indicated to provide a healthy heart [92]. Studies have recently indicated that the synthetic NMs have been detected in the environment due to their nonbiodegradable nature causing pollution, whereas the use of antioxidants derived from agrifood waste promotes sustainable waste management and promotes the nutritional profile of the preserved foods as they contain high levels of phytochemicals [93, 94].

3.4. Application of Antioxidants in Foodstuffs. Antioxidants are chemical substances that are used in food preservation to prevent oxidative processes, which are responsible for food spoilage [106, 107]. Natural antioxidants, especially those from agrifood wastes, are documented to contain essential nutrients and phytochemical compounds required for promoting human health. They are currently being explored as a possible replacement for artificial antioxidants as they are reported to be safer for human consumption, environmentally friendly and risk-free to the ecological systems [108]. Studies have indicated the presence of different phytochemical compounds such as phenolic acids, tannins, stilbene, anthocyanins and flavonols (Figure 4), which are linked to antioxidant properties [109, 110]. In addition, studies have also reported that terpenoids, saponins, glycosides, lipids and peptides are all connected to antioxidant properties [111–113]. Recently published studies have reported that some agrifood wastes possess high levels of antioxidants [11, 107, 114]. The use of antioxidants extracted from natural-based sources, such as agrifood waste for food preservation, has been reported by numerous researchers [115–119].

3.5. Meat and Dairy Products. The ethanolic extracts obtained from *Vitis vinifera* peel agrifood waste have shown remarkable results with a dosage of 1.65 $mgmL^{-1}$, which inhibited the oxidation process of the tested food products. This study detected phenolic compounds in the extracts with a high content of anthocyanins [120]. The results showed

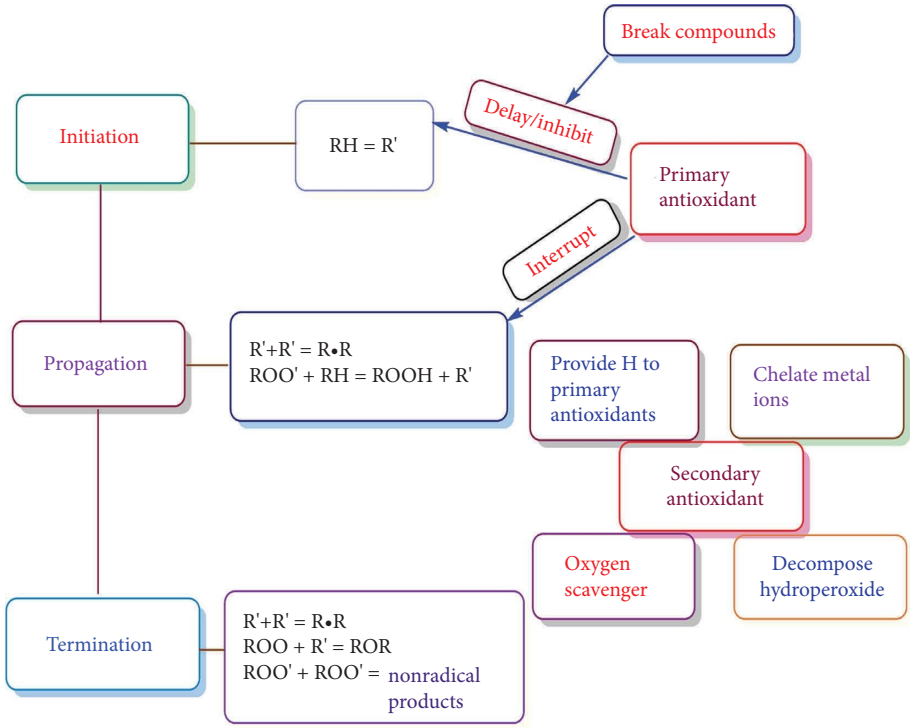


Figure 3: Lipid auto-oxidation mechanism.

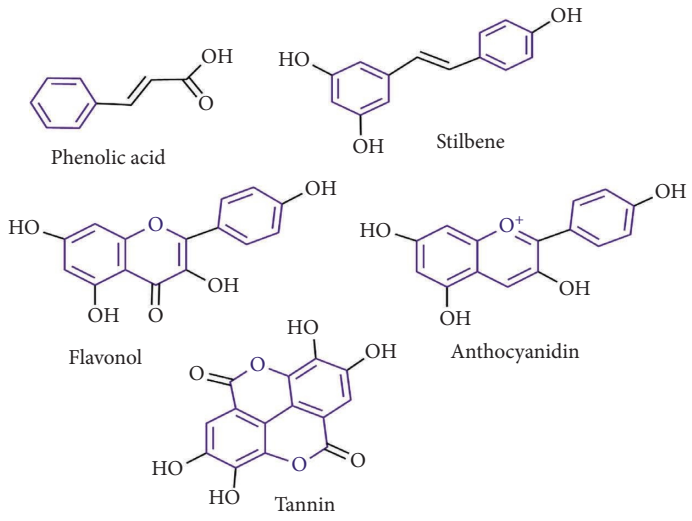


Figure 4: Examples of compounds associated with antioxidant properties.

that the extracts could be used in the development of functional food additives. A similar study carried out on *Punica granatum* seed ethanol extracts with a 25 mg·L^{-1} dosage exhibited high levels of antioxidant properties on strained yoghurt produced from sheep milk. The observed antioxidant properties were attributed to the existence of phenolic compounds [121]. In another study that examined the antioxidant characteristics of aqueous extracts of *Musa acuminata* sap, the results showed excellent antioxidant properties associated with the occurrence of caffeoylquinic and chlorogenic acids [122]. Additionally, the antioxidant characteristics of the *Musa acuminata* peels were attributed to ferulic and sinapic acids [123]. Another study explored the efficacy of *Allium sativum* peel extracts against lipid oxidation. The study found that the extract dosage of 5 mg·mL^{-1} successfully reduced lipid oxidation. The activity was attributed to the existence of phenolic compounds, such as flavonoids, tannins and β-carotene, which are responsible for excellent antioxidant properties [24]. A separate study reported the existence of high levels of phenolic compounds such as tannin and flavonoids, which are accountable for antioxidant properties in various agrifood wastes [124]. In addition, research studies conducted on *Vitis vinifera* seed waste reported that the ethanol extracts showed antioxidant

properties against cheese butter. The best results were obtained with a dosage of 100 mL of plant extract solution per 25 g, which was found to increase the shelf life of the cheese butter for 9 days [125].

Furthermore, in a study that used the aqueous methanolic extracts of *Punica granatum* peel to examine the antioxidant characteristics, the extracts contained phytochemical compounds, including phenolic compounds such as proanthocyanidins, tannins, flavonoids, oligomeric and ellagitannins [126]. These compounds are believed to be responsible for the antioxidant properties detected in *Punica granatum* peel agrifood waste. The *Musa acuminata* inflorescence bracts of ethanol extracts were tested for their antioxidant properties. The dosage range of 14–32 mg per 100 g was used against food spoilage bacteria. The characterisation study revealed the presence of phytochemical compounds, such as anthocyanin, flavonoid, phenolic acids and cyanidin 3-rutinoside. The reported phytochemical compounds were connected with the prevalence of antioxidant characteristics [127]. The agrifood wastes obtained from *Solanum lycopersicum* industry processing by-products were evaluated for antioxidant properties. Ethanol was used for the extraction process, and phytochemical compounds such as lycopene, ascorbic acid, quercetin, rutin and transcinnamic acid were successfully acquired. The tested dose used in the study was 400 and 800 mg per kg against traditional Tunisian butter oxidation. The outcome of the investigation showed that the extracts could serve as an alternative source for safeguarding butter, thereby increasing the shelf life [128].

The antioxidant studies conducted on *Litchi flower* powder with concentrations of 0.5%, 1.0% and 1.5% w/w were examined on emulsified pork meatballs for 4 weeks. The results obtained from this work showed a reduction in the growth of microorganisms and enhancement of the overall sensory characteristics [129]. The antioxidant results were attributed to the existence of the thiobarbituric acid. The agrifood wastes of *Olea europaea* leaf extract were also studied on Tabaq Mas fried ribs with concentrations of *Olea europaea* leaf extract ranging from 0.3% to 0.9% w/w for 21 days [130]. The results showed that the stored products demonstrated remarkable oxidative stability. A separate study explored the use of red pigment of *Carthamus tinctorius L.* fruit extract on colour characteristics and lipid oxidation stability on cooked pork sausages with concentrations of 0.1% and 2.0% w/w for a 1-week duration. The results observed from this study showed a decrease in lipid oxidation, a positive outcome on colour development and enhanced cooking yields of the sausages, suggesting that the synthetic nitrite additive can partly be replaced by the extract [131].

The extracts obtained from the *Malpighia emarginata* fruit peel extract were tested on beef patties for a period of 8 days. The results from this study showed that there was no change in lipid inhibition, oxidation and observed colour [132]. Similar studies have reported that the mixture of agrifood peel waste extracts from *Allium sativum*, *Cinnamomum verum*, *Syzygium aromaticum and Rosmarinus officinalis L.* EOs and *Rosa canina* was examined on Iberian cooked hams with the dosage of 1 g per kg for 150 days [133]. The outcome from this study established that there was successful lipid oxidation reduction and the protein carbonylation was controlled. Furthermore, *Origanum vulgare* extract with a dosage of 3.5 mL per kg was assessed against sheep burgers for 20 days. The colour and lipid oxidation results achieved were similar to those shown by the BHT positive control [134]. The antioxidant characteristics of *Rubus fruticosus* peel extracts with doses of 30, 60 and 90 mg per kg were tested on cooked beef sausages for 30 days. The results showed that the extract could be used as an alternative substitute for the sodium nitrite preservative ingredient [135]. The antioxidant properties of *Solanum lycopersicum* peel powder were tested on pork patties with doses of 30, 60 and 90 mg per kg for 14 days [136]. The results achieved had a lower reactive rate comparable to thiobarbituric acid.

3.6. Microbes Associated With Food Spoilage. Food spoilage by microorganisms is a serious global issue, with 25% of the produced food getting spoiled. The main agents that promote food loss are yeasts and bacteria that contribute to food decay and foodborne diseases [137]. These species of microorganisms contain unique properties that enable them to survive under various food processing and storage conditions. The bacterial agents that are reported to cause food rotting include *Bacillus species*, *Listeria species*, *Clostridium species*, *Enterococcus species*, *Staphylococcus species*, *Lactococcus piscium*, *Pseudomonas species*, *Passiflora species* and *Shewanella putrefaciens* [138–142]. Conversely, the species of yeasts that are known to cause food spoilage are *Zygosaccharomyces*, *Candida krusei*, *Aspergillus*, *Penicillium* and *Lactobacillus* [143–145]. This suggests the development of effective, convenient and reliable storage facilities to extend the shelf life of food products, such as the use of natural antimicrobials, is of paramount importance.

3.7. Benefits of Antimicrobials. Antimicrobials obtained from natural food additives are currently gaining preference over the antimicrobials obtained from synthetic food additives as they provide additional health benefits and pose lower risks. Studies indicate that phytochemicals such as eugenol, carvacrol and cinnamaldehyde found in herbs and spices possess preservation properties, and they also promote human health due to their anti-inflammatory and antioxidant properties [146, 147]. Furthermore, these phytochemical compounds have also been associated with the reduction in chronic illnesses such as cancer and heart-related diseases [147, 148]. Studies carried out on meat, fish and dairy products preserved with EOs obtained from *Olea europaea* and *Rosmarinus officinalis* leaf extracts have shown success in inhibiting the growth of spoilage microbes [149, 150]. The overall quality of the preserved food products was maintained, suggesting that natural antimicrobials offer an effective and safe option for food preservation. Studies have also indicated that consumption of food preserved with natural antimicrobials facilitated the reduction in foodborne illness, allergies and infections caused by synthetic food

preservatives [151, 152]. In addition, the environmental and ecological concerns associated with natural antimicrobials are less hazardous as they are biodegradable unlike synthetic additives, which are persistent in the environment, thereby causing environmental pollution and threatening the existence of ecosystems [153–155].

3.8. Antimicrobial Mechanisms. The use of extracts obtained from natural sources as preservatives has increased recently amongst consumers. The increase had been necessitated by the rising health concerns related to the consumption of food preserved with synthetic additives. The food preserved with natural antimicrobials is reported to be much safer than food preserved with synthetic additives. Natural antimicrobials preserve the food while maintaining its quality for consumer satisfaction. These natural antimicrobials have a high concentration of phytochemicals, which are responsible for antimicrobial characteristics. Studies indicate that the mechanisms used by antimicrobials in food preservation involve the biochemical interactions that disrupt microbial growth and reduce survival capacities. Researchers have found that EOs obtained from various parts of plants contain high levels of bioactive compounds such as terpenes and phenolic compounds, which are capable of infiltrating microbial membranes, thereby compromising membrane integrity and operations, leading to cell rupture and death [156]. There are several mechanisms by which natural antimicrobial preservatives interact and disrupt the bacterial cells. These interactions are generally based on their capacity to interrupt cellular integrity and metabolic functions through a number of modes of action, such as coagulation of cytoplasmic components, degradation of the cell wall, inhibition of cytoplasmic enzymes, leakage of cellular constituents and ion antimicrobial activity as shown in Figure 5.

The initial mechanisms, which involve degradation of the cell wall, are recognised as the most significant stage in the antimicrobial action exhibited by natural preservatives. Studies indicate that the structural arrangement of bacterial cells is generally disrupted due to the presence of phytochemicals in EOs. Multiple studies report that compounds found in EOs infiltrate and interrupt the peptidoglycan layers of bacterial cell walls, especially Gram-positive strains that do not contain a defensive outer membrane [157, 158]. The degradation exposes the bacterial cells, thereby making them prone to further attack by antimicrobial agents, leading to cell rupture. Studies indicate that EOs, especially those derived from *Allium sativum* and *Ocimum tenuiflorum*, successfully compromised and degraded the cell wall of bacterial cells [159]. Additionally, EOs extracted from *Cinnamomum verum* caused cell malfunctions and structural changes, resulting in cell interruption and death [156].

Coagulation of the cytoplasm occurs once the cell wall has been disrupted. The EOs and other significant phytochemicals induce alterations in the cytoplasmic membrane, resulting in cytoplasmic coagulation. It is reported that proteins and nucleic acids found in the cytoplasm get denatured and aggregated due to the interaction of EOs and the cytoplasmic membrane [160]. The subsequent coagulation process forms part of cell morphological studies that can be confirmed through transmission electron microscopy (TEM), which indicates the cytoplasmic compaction and the loss of cellular integrity [161].

Inhibition of cytoplasmic enzymes is another significant mechanistic pathway in which antimicrobial compounds act. It is documented that EOs obstruct the metabolic routes, for instance, those used in energy production and lipid biosynthesis. The obstruction involves essential enzyme activities such as cellular respiration and principal metabolic functions [162]. Studies have revealed that EOs significantly reduce enzymatic activities, resulting in a reduction of adenosine triphosphate (ATP), leading to cellular malfunctions and death [163, 164]. The inhibiting enzymes also interrupt significant biosynthetic pathways required for microbial replication and survival besides affecting cellular growth. Studies have shown that saponins demonstrate antimicrobial effects and suppress the activities of enzymes responsible for microbial virulence, thereby inhibiting the increase in bacteria that causes food spoilage [165, 166].

Furthermore, the direct effect of the compromised cell wall and cytoplasmic membrane leads to leakage of the cytoplasmic membrane. EOs assist in the dispersion of constituents such as ions, proteins and metabolites from the cell, leading to disruption of osmotic balance and resulting in cell death [167, 168]. Numerous studies have reported the leakages, suggesting the versatility of EOs in the creation of pores or inducing membrane disruption, resulting in the uncontrollable release of delicate intracellular contents such as essential K^+ and Na^+ ions. The loss of essential ions drives homeostasis to a level where it becomes unmanageable [162, 169]. Therefore, the continued loss of these vital constituents weakens the bacterial cells' capability to sustain important biochemical processes.

Conversely, ion antimicrobial action represents a more delicate mechanism of activity involving imbalances of precise ions inside the bacterial cell that is significantly affected. Antimicrobials generally determine the proton motive force, which is significant for ATP production, an energy-dependent process required for cellular respiration [163]. The direct disturbances realised in EOs result in significant alterations in the proton concentrations across membranes, resulting in a harsh environment for microbial cell existence. Additionally, studies indicate that changing the membrane electrochemical gradient facilitates the leakages of essential nutrients, thereby creating difficulties in nutrient absorption, leading to a cytotoxicity mechanism in a bacterial cell environment [164, 167]. Studies have shown that bioactive compounds such as monoterpenes and aromatic compounds prevent the growth of bacterial strains such as *Escherichia coli* and *Staphylococcus aureus*, which are known to cause food spoilage [162]. They involve interactions through competitive inhibition of binding sites on bacterial cell walls or blocking transportation of ions, resulting in impairing both nutrient absorption and detoxification of hazardous metabolites [170, 171].

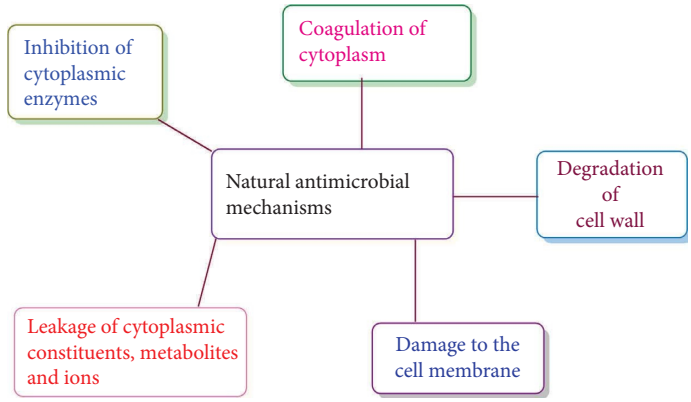


Figure 5: Summary of various antimicrobial mechanisms.

3.9. Applications of Antimicrobial. Recently, there has been an increase in interest in the exploration of antimicrobials from plants as potential food additives. The studies have shown that the use of plants, such as agrifood wastes, for food preservation poses fewer health risks compared with synthetic ones [172]. Agrifood wastes contain abundant phytochemical substances that are associated with the provision of human health benefits. These phytochemicals are known to inhibit oxidative stress, cancer and cardiovascular diseases due to the presence of excellent antioxidant properties that are capable of stabilising free radicals in the body [36, 173, 174]. Antimicrobials from plants consist of phytochemical substances such as phenolics, EOs, terpenoids and other phytochemicals, which are responsible for extending the shelf life of foods by reducing the growth of microbes as indicated in Table 3 [175].

3.10. Bakery Products. Agrifood wastes from vegetables and fruits, such as *Malus domestica* fruit and waste discarded from fruit processing industries, are recognised as rich sources of antimicrobials and phytochemicals [176]. The use of agrifood wastes is recommended in promoting health products due to the presence of bioactive compounds that retain the antimicrobial and anti-inflammatory properties [177]. Other studies have evaluated the incorporation of antimicrobials derived from agrifood wastes in biodegradable packaging materials to increase the shelf life of food and overcome environmental issues that arise due to waste disposal [178, 179].

A study evaluating the antimicrobial characteristics of extracts obtained from *Citrus sinensis* peel and *Punica granatum* peel agrifood waste on bakery products against five spoilage bacteria, *Serratia marcescens*, *Escherichia coli*, *Staphylococcus aureus*, *Bacillus subtilis*, *Bacillus cereus and Klebsiella pneumoniae*, reported an extended shelf life of the cake products because the growth of the spoilage bacteria was hindered [180]. This suggests that these two agrifood wastes can be used to replace synthetic chemicals used in industries during food processing and manufacturing. A similar study assessing the *Musa acuminata* peel powder for the preservation of bakery products against the spoilage microorganisms demonstrated excellent antimicrobial properties, enhanced mineral levels and great enhancement of the sensory characteristics of the cake products [181]. In an investigation carried out by Abdel-Hameed and coworkers, which examined the antimicrobial properties of oil extracts and powder obtained from *Carica papaya* seeds on chocolate cakes against spoilage bacteria, *Bacillus subtilis*, *Staphylococcus aureus*, *Enterococcus faecalis*, *Pseudomonas aeruginosa*, *Bacillus cereus*, *Salmonella spp.*, *Candida albicans and Aspergillus spp.*, reported the suppression of the growth of microbes, increased shelf life and promoted the flavour and nutrient levels of the cakes [182].

3.11. Meat Products and Dairy Products. In a study aimed at exploring the antimicrobial properties of *Allium cepa* food waste, the waste extract and powder were tested on meat and dairy products. The *Allium cepa* peel powder and extracts were examined on meat and beef meatballs, and the results showed that the powder and extracts extended the shelf life of both the meat and beef meatballs. The activity of the powder and extracts was connected to the existence of high levels of phenolics and flavonoids in the *Allium cepa* [183, 184]. A similar study measured the efficacy of *Citrus limon* peel and *Citrus sinensis* peel powders for the antimicrobial properties against meat. The results of the study showed that the powder slowed the multiplication and growth of spoilage microorganisms. The results suggest that agrifood wastes are a possible replacement for synthetic antimicrobials used in meat processing products [185]. The extract obtained from *Punica granatum* peel applied to buffalo meat drastically decreased the colony-forming units of the spoilage bacteria. Similar results were obtained when *Punica granatum* powder was added to beef meat, leading to a decrease in total bacteria counts, lipid oxidation and pH values, thereby increasing the shelf life of the meat [186, 187].

Furthermore, in a study that evaluated the antimicrobial efficacy of *Satureja horvatii* EOs on pork meat using dosages of 10 and 20 $mg{\cdot}mL^{-1}$, the results showed total inhibition of *L. monocytogenes* spoilage microbes [188]. A similar study used EOs obtained from bay leaf for the preservation of sausages with a dosage of 0.1 per 100 g. The results indicated a 2.8 log (CFU per g) reduction in the total coliforms [189].

Table 3: Antimicrobials obtained from agrifood waste in food storage and preservation.

Antimicrobials	Studied microbes	Concentration	Results obtained	Preserved food	References
Thymus vulgaris EOs	*L. monocytogenes*	0.8% and 1.2%	Reduced colonies to two counts	Minced fish	[200]
Satureja horvatii OEs	*L. monocytogenes*	10 and 20 mg·mL^{-1}	Complete inhibition	Pork meat	[188]
Laurus nobilis leaf EOs	*coliforms*	0.1 g per 100 g	2.8 log CFU/g reduction in total colonies	Sausages	[189]
Origanum vulgare EOs	*L. monocytogenes*	500 ppm	Growth rate reduced by 19 per cent	Ham	[190]
Cinnamomum verum EOs	*L. monocytogenes*	500 ppm	Reduction in growth rate by 10 per cent	Ham	[190]
Castanea sativa shell	*C. jejuni*	2 mg/g	Inhibited *C. jejuni* to 3 log CFU/g	Chicken meat	[191]
Olea europaea leaf extracts	Total viable count	2% (w/v)	Reduced to 2 log CFU/g initial population	Raw, peeled, and undeveined shrimp	[204]
Citrus limon EOs	*E. coli*	0.1 mL/100 g	Decrease to 1.7 log CFU/g in *E. coli*	Chocolate	[201]
Verbena officinalis EOs	*Monilinia laxa*, *M. fructigena*	1000 ppm	Reduction in brown rot	Peaches	[203]
Thymus vulgaris EOs *Citrus limon* EOs	*E. coli*	5000 ppm	A 5 log CFU/g decrease was observed	Apple juice	[202]
Clove essential oil	*E. coli* *S. aureus* *P. aeruginosa*	0.5%–2% v/w	Decreased microbial load by 3–4 log CFU/g Effective against bacterial multiplication	Chicken meat	[155]
Thymus vulgaris oil	*E. aerogenes*	0.3% v/w	Excellent bactericidal activity decreased microbial loads by 3 log CFU/g	Meat analogue	[19]
Beta vulgaris	*Listeria spp.* *Bacillus spp.*		Lowered microbial growth by 1.3 log CFU/g	Pork meat	[205]
Rhus coriaria extract	*S. aureus* *E. coli*	1%–2% w/w	Best antibacterial activity	Cured meat	[206]
Origanum vulgare oil	*S. enteritidis*	0.6%–0.9% v/w	Reduced bacteria counts by 2 log CFU/g	Mutton	[207]
Allium sativum extract	*Salmonella spp.*	0.5%–1% v/w	Reduced microbial load by 2 log CFU/g	Beef	[208]
Citrus limon extract	*E. coli*	2.5% w/w	Antibacterial activity	Meat products	[209]
Hibiscus sabdariffa extract	*S. aureus*	1% w/w	Antibacterial activity	Meat products	[210]
Tamarindus indica extract	*E. coli*		Antibacterial activity	Meat products	[211]
Cuminum cyminum extract	*S. aureus*	0.5% w/w	Antibacterial activity; lowered microbial load	Processed meat	[212]
Nandina domestica	*S. aureus*	0.1%–0.5% w/w	Reduced microbial load	Chicken meat	[213]

Additionally, ham was preserved with natural antimicrobials obtained from *oregano* and *cinnamon* with a dosage of 500 mg·L^{-1}. It was reported that the growth of *L. monocytogenes* bacteria was significantly reduced by 10 and 19% by *cinnamon* EOs and *oregano* EOs, respectively [190]. Similarly, another study tested the effectiveness of *chestnut shell* antimicrobial extracts for the preservation of chicken meat. The study employed a dosage of 2 mg per gram. It was found that antimicrobial extracts successfully decreased the growth of *C. jejuni* bacteria from 1×10^5 to a log 3 CFU per g [191].

The use of agrifood wastes in dairy products has been reported by a number of researchers. *Citrus limon* peel extract was used to safeguard milk products against *Bacillus cereus, Staphylococcus aureus, Listeria monocytogenes, Bacillus subtilis, Escherichia coli, Salmonella typhimurium, Pseudomonas aeruginosa, Candida albicans* and *Aspergillus fumigatus* contaminations.

These species of microbes cause spoilage of milk and dairy products through a number of mechanisms such as production of toxins, enzymatic activities and changing organoleptic properties of the dairy products [192–194]. The shelf life of the milk products was prolonged, and the microbial load was considerably reduced [195]. The increase in shelf life and reduction in the microbial load were linked to the presence of phytochemical compounds such as phenolics and flavonoids that are known to promote antimicrobial properties in plants. An independent related study evaluated the antimicrobial efficacy of *Punica granatum* peel extract on *Listeria monocytogenes, Pseudomonas aeruginosa, Klebsiella pneumoniae, Aspergillus niger* and *Candida glabrata* that cause rotting of yoghurt smoothies. The study reported that the microbial load of the smoothies was significantly reduced [196]. These results suggest that *Punica granatum extract* consists of phytochemical substances responsible for suppressing the growth and multiplication of the bacteria and could be used in processed dairy food products. A similar study tested the antimicrobial properties of *Persea americana* peel extract on mayonnaise. The results showed that the growth of *Staphylococcus aureus, Staphylococcus epidermidis* and *Escherichia coli mi*crobes was completely inhibited [197]. Despite the activity exhibited by the *Persea americana* peel extract, the chemical and physical characteristics of the tested dairy products remained the same. The results achieved in the study indicate that the *Persea americana* peel is a rich source of phytochemical compounds, which could be used to boost the dairy processing industries and substitute synthetic additives.

The antimicrobial properties of an extract derived from *Punica granatum* peel waste were used on butter against food-rotting microorganisms. It was observed that the microbial load reduced drastically and increased the shelf life of the tested butter [198]. The results could be connected to the existence of the phytochemical substances in *Punica granatum* peel. Additionally, the outcome suggests that the agrifood waste could be used in dairy manufacturing and processing industries. Another study examined the antimicrobial characteristics of the agrifood residue extract on both meat and dairy products against spoilage bacteria [199]. The results showed that the extracts reduced the growth and multiplication of the spoilage microorganisms. This suggests that the residues could be used for the storage of foodstuffs, thereby increasing the shelf life.

3.12. Other Foodstuffs. Researchers elsewhere have investigated the efficacy of antimicrobial extracts on other foodstuffs. EOs obtained from thyme were assessed for the preservation of minced fish with dosages of 0.8% and 1.2% [200]. The results attained from this study indicated a total reduction in *L. monocytogenes* from 100 colonies to 2 counts. The strong antimicrobial activity was linked to the presence of phytochemical compounds found in thyme. Similarly, EOs obtained from *lemon* peel were reported to reduce *E. coli* in tested chocolate from 5×10^7 to 1.7 log CFU per g with a dosage of 0.1 mL per 100 g [201]. Again, apple juice preserved with natural antimicrobials obtained from *thyme* EOs and *lemon* EOs with a dosage of 5000 mg·L^{-1} had reduced *E. coli* from 3×10^7 to 5 log CFU per g [202]. EOs obtained from *vervain* with a dosage of 1000 mg·L^{-1} were indicated to decrease the growth of *Monilinia fructigena* on peaches [203].

The antimicrobial characteristics of three extracts obtained from *Punica granatum*, *Solanum tuberosum* and *Malus pumila* peel agrifood waste were tested on chicken meatballs against spoilage bacteria. The results showed that the extracts reduced the growth of bacteria [214]. The antimicrobial characteristics of four powders derived from *Musa sapientum* peel, *Citrus sinensis* peel, *Citrus limon* peel and *Citrus paradisi* peel agrifood wastes were tested on chicken meatballs against the destructive bacteria *Staphylococcus aureus*. The results obtained from the study showed lower microbial loads upon adding the powders to the meatballs [215].

3.13. Phenolic Compounds in Some Agrifood Wastes. Several studies have detected and singled out phenolic compounds and linked them to the prevalence of antimicrobial properties in agrifood waste. The most identified and reported phenolic compounds are shown in Figure 6. A study carried out on *Capsicum annuum* waste demonstrated bactericidal and bacteriostatic properties by inhibiting the growth of several microorganisms including *Escherichia coli, Staphylococcus aureus, Salmonella typhimurium, Klebsiella pneumoniae and Bacillus cereus*. The results observed in this study were linked to the presence of the protocatechuic acid [216, 217]. A similar study evaluated the antibacterial properties of the skinned onions against microorganisms such as *Staphylococcus aureus, Pseudomonas aeruginosa, Proteus vulgaris, Escherichia coli, Shigella flexneri and Lactobacillus casei var. Shirota*, *drug-resistant Escherichia coli or carbapenem-resistant Pseudomonas aeruginosa*. The results showed that the growth and multiplication of the studied microbes were suppressed. The observed activity was attributed to the occurrence of phenolic compounds quercetin and glucosides such as quercetin aglycone and anthocyanin [218, 219].

Other research studies have connected the existence of caffeic acid in *Carica papaya*, *Citrus limon*, *Malus domestica* and *Punica granatum* agrifood wastes as responsible for the

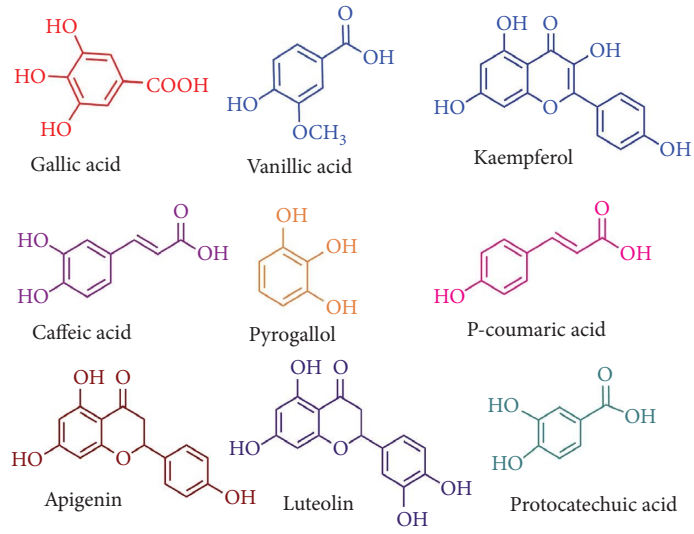


Figure 6: Phenolic acids linked with antimicrobial properties in agrifood wastes.

antibacterial and aflatoxin reductions in foods. These wastes demonstrated antimicrobial characteristics by slowing the growth and multiplication of *Escherichia coli and Klebsiella pneumoniae*, *Aspergillus flavus and Aspergillus parasiticus* [220, 221]. Conversely, a study conducted on unripe *Solanum lycopersicum* reported that antibacterial and decreased aflatoxin characteristics are connected to the presence of vanillic acid. The extract of the unripe *Solanum lycopersicum* reduced the multiplication of *carbapenem-resistant Enterobacter hormaechei*, *Aspergillus flavus* and *Aspergillus parasiticus* microbes [222, 223]. Studies conducted on *Brassica oleracea* leaves and flowers showed antibacterial properties against *Staphylococcus aureus*, revealing a significant reduction in the studied microbes, indicating the antimicrobial characteristics. The results obtained were attributed to the occurrence of gallic acid [168]. Likewise, another study assessed *Cactaceae* pear peel extract for antimicrobial properties and established that the bacterial colonies of the *Candida albicans* population and *Staphylococcus aureus* were drastically reduced. The results observed were connected to the presence of the pyrogallol compound [168, 224]. Kaempferol phenolic acid was identified and isolated from *Vitis vinifera* peels and reported to reduce the growth of *Staphylococcus aureus* [225, 226].

The antibacterial studies conducted on *Passiflora edulis* fruit pulp and seeds, *Olea europaea* leaves and *Ananas comosus* peels against *Bacillus cereus*, *Escherichia coli* and *Pseudomonas aeruginosa* gave positive results towards the evaluated microbes. The observed results were connected to the presence of p-coumaric acid, oleuropein and apigenin and luteolin for phenolic acids for *Passiflora edulis* fruit pulp and seeds, *Olea europaea* leaves and *Ananas comosus* peels, respectively [17, 227–229].

3.14. Challenges Associated With the Usage of Natural Additives. Despite high demand by consumers for safe and healthy foods, studies indicate that there are some setbacks associated with the usage of natural food additives [230, 231]. Despite the fact that additives from natural sources provide significant benefits such as colorants, preservatives and flavouring ingredients, they are obtained through extraction and isolation techniques using chemical solvents [232, 233]. Researchers have indicated concerns associated with the use of solvents, especially in traditional extraction techniques. Most of the chemical solvents are a threat to human health, and as such, bioactive compounds require thorough purification before they can be used as food additives. Solvents also pose environmental pollution risks [234, 235].

The scaling up of natural additive applications has encountered several challenges, including sustainability, stability and cost-effectiveness [236, 237]. Furthermore, the extraction methods and the geographical origin of the raw materials can also affect the antimicrobial properties of the waste extracts. In most cases, the use of natural antimicrobial additives is carried out at the household level without proper exploration of their health and safety and possible side effects [230]. The absence of universal regulations and the collision of study outcomes have promoted disputes regarding the incorporation of natural food additives [238]. To resolve these challenges, there is a need to continue inventing smart solutions, for instance, 'nanoencapsulation' additives, and create composite and functional food additives [231, 239].

4. Conclusion

The present study aimed at assessing the latest developments in antimicrobials and antioxidants from agrifood waste as an alternative to replace synthetic food additives. The results attained in the literature reviewed in this study have shown that the agrifood waste, peels and seeds are a rich source of phytochemical compounds. The antioxidant and antimicrobial studies carried out on agrifood waste extracts on foods such as meat, milk and bakery products have shown excellent results in preventing oxidation processes. Furthermore, the shelf life of the tested bakery products was

successfully extended and the growth of spoilage microbes was completely hindered. The activity of the extracts was attributed to the existence of phytochemical compounds in the agrifood wastes. The results suggest that agrifood waste phytochemical compounds are a possible option to replace synthetic additives. Environmentally, the use of agrifood waste promotes sustainable waste management through the development of food preservatives that do not pose human health and environmental concerns. The conversion of agrifood waste into antimicrobials and antioxidants has made a positive impact towards combating pollution issues associated with agrifood waste disposal challenges, as well as mitigating climate change concerns caused by the emissions of GHGs produced in dumping sites or landfills. In addition, the use of agrifood waste offers several benefits through valorisation. Dealing with the setbacks caused by agrifood waste through sustainable and innovative techniques is significant for ensuring environmental protection and food security.

Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Joel B. Njewa wrote the original draft and wrote, reviewed and edited the manuscript. Maurice Monjerezi wrote the original draft and wrote and edited the manuscript. Felix D. Kumwenda wrote the original draft, wrote, reviewed and edited the manuscript. Jimmy Sumani wrote the original draft and reviewed and edited the manuscript.

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