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REVIEW ARTICLE

The beneficial effects of citrus peel waste and its extract on fish performance and health status: A review

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Abstract

Food production and processing in developing countries produce a huge amount of fruit waste by-products, which is costly and pose detrimental effects on the environment. Proteins, lipids, starch, micronutrients, bioactive compounds and dietary fibres are found in many of these fruit wastes. Among fruit wastes, citrus fruits play an important role in generating a wide range of health benefits. Citrus L. of the Rutaceae family are common fruits cultivated and consumed globally both as fresh fruits and as a juice. Citrus peel wastes (CPW) are considered the main by-products, with an average of 60% of processed fruits; hence, CPW have a promising role in the food production industry. CPW contain high concentrations of polyphenol and essential oils, which have nutritional importance and pharmaceutical usage. There is a concern on the increasing prevalence and incidence of different fish infections and a growing interest in shifting from synthetic to natural antimicrobial agents, leading to the use of citrus peel wastes for identification of novel compounds for use as fish feed additives. Although the antimicrobial properties of EOs have been reviewed extensively, the antimicrobial properties of citrus peels oil have not been extensively discussed. In fish farming, feeding strategies that employ phytochemicals as modulators of immunological and physiological responses such as growth, antioxidant activity and gene expression have received attention. In the past years, several studies have reported positive results of using citrus peel extracts as a nutritional additive in aquafeeds. Recently, these dietary functional feed additives have been evaluated and reported to increase disease resistance and improve fish growth, animal welfare and feed utilization. This review elucidates the global production, bioactive compounds, natural sources, chemical structures, physical properties, practical applications of citrus peel wastes and extracts as a desirable and sustainable route in fish nutrition.

KEYWORDS
aquafeed additive, citrus peel wastes, growth performance, health status, phytochemicals

1 | INTRODUCTION

Sweet orange (*Citrus sinensis*), tangerine or mandarin (*Citrus reticulata*), grapefruit (*Citrus vitis*), lime (*Citrus aurantiifolia*) and lemon (*Citrus limon*) are among the most widely cultivated and consumed citrus fruits in the world. Citrus fruits have a distinct flavour, taste and fragrance and are high in vitamins and minerals, such as vitamin C, folic acid, carotenoids, potassium, pectin and fibre. Citrus fruits also contain active ingredients such as polyphenolic compounds (e.g. phenolic acid and flavonoids) (Guimarães et al., 2009; Manthey & Grohmann, 2001). Antioxidants, anti-inflammatory and antibacterial properties are all provided by these bioactive substances. These substances can also help to alleviate the symptoms of some significant chronic diseases, such as cardiovascular disease and age-related muscle degeneration. Furthermore, several of these compounds contain antigenotoxic properties, which prevent the genetic material in cells from being damaged (López-Romero et al., 2018). As a result, they play an important physiologic function in human health and vitality (Pellegrini et al., 2003; Peterson et al., 2006).

Citrus crops are grown throughout the world in tropical and subtropical regions. They were initially grown in the warm southern slopes of the Himalayas in northern India and Myanmar. China, Brazil, India, Mexico, Spain and the United States are the top citrus-producing countries, accounting for nearly two-thirds of global production. In 2019, citrus plant production reached 157 million tons, with 60% used as fresh fruit for human consumption and the other 40% for industry (World Data Atlas, 2021).

Citrus peel wastes (CPW) are the most common by-products, accounting for 60% of all processed fruits; hence, CPW have a promising role in the food industry (Chavan et al., 2018). They have a high concentration of polyphenol and essential oils, both of which have nutritional and pharmaceutical use. Traditionally, CPW have been used as low-value feedstuffs for ruminant animals or as organic soil fertilizer. An excessively high load of CPW may compromise soil fertility or cause damaged aquatic ecosystems because of the antibacterial activities of the essential oils. CPW is generally discarded by either incineration or landfilling, causing environmental pollution and economic loss. As a result, the treatment and processing of these readily available and inexpensive wastes is a promising approach to saving alternative sources of nutrients for human food and animal feed while also keeping the environment clean (Satari & Karimi, 2018; Zema et al., 2018).

Citrus by-products have been investigated as an unconventional source of vital nutrients, such as soluble sugars, fibre, pectin, polyphenol and essential oils. Previous studies have explored the use of citrus by-products in food, pharmaceuticals and biotechnology processes. This paper presents a review of the nutritional and economic benefits of using citrus peel wastes as a viable source of vital nutrients and high-value bioactive compounds for improvement of fish health.

2 | GLOBAL CITRUS PRODUCTION

Citrus fruits were first cultivated in Southeast Asia, then introduced and disseminated over Africa, southern Europe, the Mediterranean and the Americas during the Middle Ages (Gmitter & Hu, 1990; Webber, 1967). Citrus production has grown rapidly in more than 140 countries throughout the tropical and subtropical regions of the world because of efficient growing, harvesting and processing techniques (Baldwin, 1993; Ladaniya, 2008a).

Oranges, tangerines, mandarins and grapefruit accounted for 51.9%, 32.6%, 7.2% and 8.34% of global production respectively. Approximately 68.44% of citrus is consumed, with the remaining 21.5% used for processing. Mostly, sweet oranges (*C. sinensis*) account for over 70% of total citrus production and consumption globally, with one-third utilized for juice production and the rest marketed as whole fruit (Figure 1; FAO, 2017; USDA, 2019). Citrus production in China increased to 40 million tons in 2017, more than doubling that of Brazil, the world's second-largest citrus producer. In China, the most popular citrus fruits are tangerines, oranges and grapefruits. The two biggest citrus producers in America, particularly oranges, are Brazil and the United States. After China and Brazil, India is the third largest producer of citrus fruits, with oranges accounting for 88% of total production (Figure 2; FAO, 2019; Ladaniya, 2008b).

3 | THE STRUCTURE OF CITRUS FRUITS

The citrus fruit consists of the peel or rind (the flavedo—the outer coloured part that has either yellow or orange colour, and the albedo—the interior white spongy part), the pulp or rag, and seeds, which make up to 10%, 17%, 71% and 2% of the total fruit weight respectively.

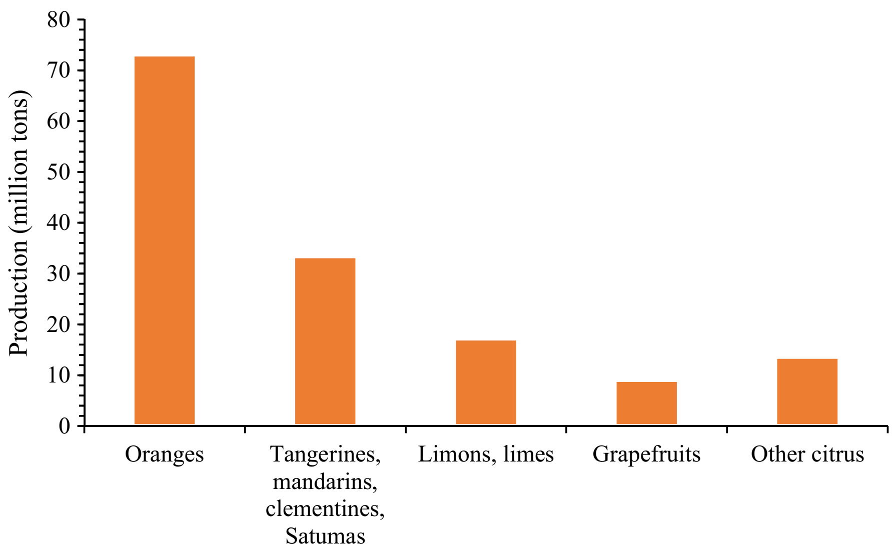

FIGURE 1 Global citrus fruit production in 2017 (FAO STAT, 2017).

Mostly, 87% of the citrus fruits is water, and the rest consists of several micronutrients (10% minerals, 5% essential oils, 3% fats, 9% proteins, 11% fibres, 16% citric acids, 21% pectin, 10% glucosides and 15% pentosans; Mahato et al., 2018; Oikeh et al., 2013). The edible components of the citrus are the pulp and juice, while the non-edible parts include the segment walls, peel, pith residues and seeds.

4 | CITRUS BY-PRODUCTS (WASTES)

Citrus by-products are the solid material that remain after juice extraction from the fruits. These wastes include the peel, pulp, rag and seeds (Figure 3). Citrus juice yield and citrus by-products chemical composition depend on the juice extraction method, citrus fruit, climate, and location of cultivation, and amount of water that remained after processing (Tables 1 and 2). Citrus by-products represent 50%–70% of the total treated citrus weight. Citrus by-products contain 60% peel, 30% pith residues and 10% seeds (Bampidis & Robinson, 2006; Chavan et al., 2018; Marín et al., 2002). Also, these by-products contain high moisture (85%) and organic matter content. Moreover, they are a rich source of natural valuable compounds such as soluble sugars (glucose, fructose and sucrose), carbohydrates (cellulose, starch, pectin and dietary fibres), proteins, organic acids (citric, malic and oxalic acids), lipids (linolenic, oleic, palmitic and stearic acids), essential oils (D-limonene, α-terpinolene and α-pinene), carotenoids (carotene and lutein), vitamins (vitamin C and vitamin B complexes) and polyphenols (flavonoids and phenolic acids; Mahato et al., 2018).

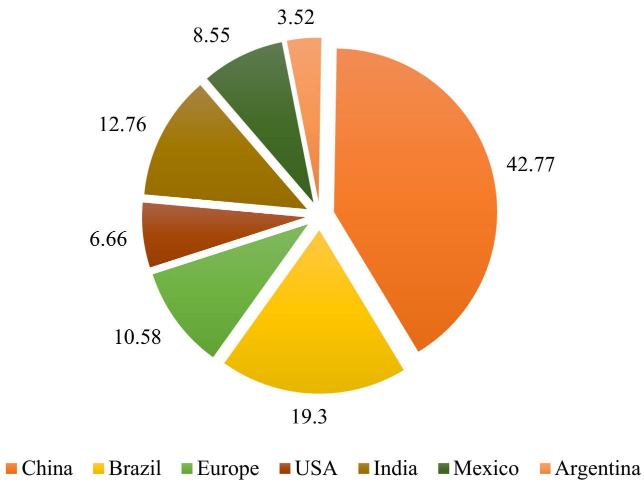

FIGURE 2 Citrus production by country in 2019 (in metric tons) (FAO, 2019).

Citrus wastes have been either directly dumped in landfills and rivers or burned, which poses an important environmental issue of soil degradation. Soil is degraded due to the destruction of soil flora by the antimicrobial properties of the essential oils from the citrus peels and oxygen depletion of water.

Citrus wastes may be used as an agricultural fertilizer or a low nutritional value animal feed for ruminants, chickens and pigs. Nevertheless, the drying process for the citrus wastes is costly and energy intensive. The low nutritional value of citrus wastes not only limits their use as an animal feed, but also are characterized with low palatability for animals, mainly attributed to the bitter flavour, foul odour and high acidity of limonene. Hence, to make the most of the use of citrus wastes, the removal of oils serves as an indispensable step in the processing. Currently, a biorefinery framework capitalizes on the value of citrus wastes, either by extracting high-value products and food items, or by recycling such renewable resources using low-cost techniques to produce valuable products (Panwar et al., 2019).

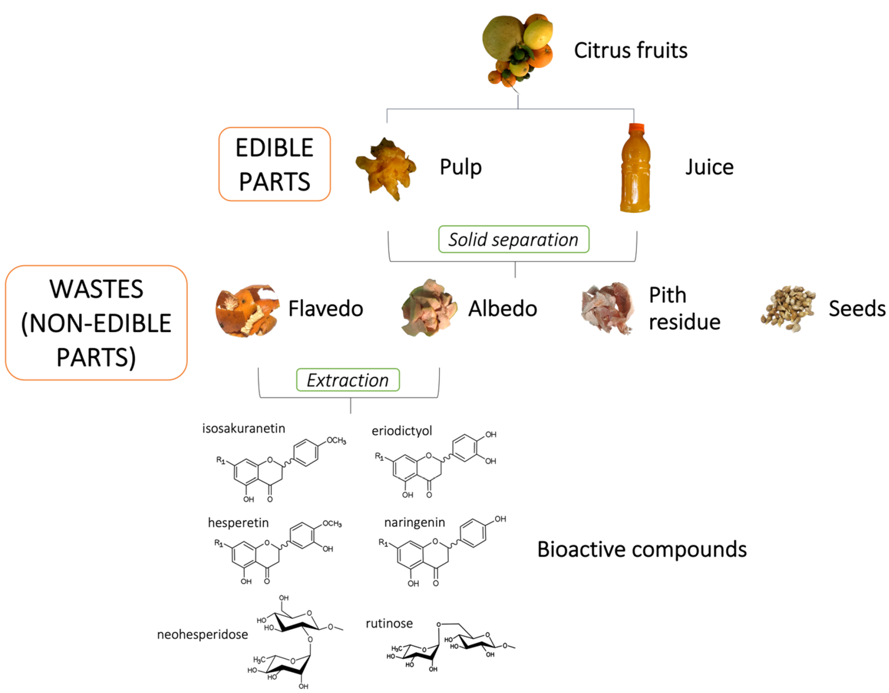

FIGURE 3 Different citrus wastes and selected extracts thereof from citrus fruits processing.

TABLE 1 Nutritive value of different citrus wastes (expressed as % dry basis)

Citrus wastes	Ash	Sugar	Fat	Protein	Pectin	Lignin	Cellulose	Hemicellulose	Sources and references
Lemon peels	2.5	6.5	1.5	7.0	13.00	7.56	23.06	8.09	Marín et al. (2007)
Lemon pulp	2.5	9.0	3.1	8.7	22.53	7.55	36.22	11.05	
Orange peels	1.7–2.6	9.6–41.4	3.9–4.0	7.9–9.1	14.4–23.02	1.0–7.52	16.2–37.08	11.04–13.08	Marín et al. (2007); Mamma et al. (2008)
Orange pulp	2.6	6.0	1.5	6.6	12.07	7.51	24.52	7.57	Marín et al. (2007).
Kinnow mandarin waste	3.2	31.6	n.d.	5.8	22.6	0.6	10.1	4.3	Oberoi et al. (2011)
Mandarin peel waste	3.0	21.6	n.d.	n.d.	14.2	8.9	20.8	17.2	Boluda-Aguilar et al. (2010)
Grapefruit Peels	3.3	n.d.	n.d.	n.d.	16.1	8.2	19.8	18.3	Boluda-Aguilar and López-Gómez (2013)

Abbreviation: n.d., not detected.

5 | BIOACTIVE COMPOUNDS OF CITRUS WASTES

Citrus wastes contain a wide variety of biologically active compounds, such as essential oils, pectins, carotenoids and limonoids that can be extracted and used in food, feed, pharmaceutical and cosmetic industries. There are certain limitations to extracting these valuable compounds such as the lack of an efficient and low-cost extraction technique, among others, that preserves the biological activity of the extracted compounds. The process of extraction has a significant impact on the biological activity of the extracted compounds (Panwar et al., 2019). Furthermore, the toxicity of the organic solvents used for the extraction of the lipophilic compounds, such as hexane, petroleum ether and diethyl ether, poses a health issue. The choice of the extraction technique depends on the nature of the biological compounds to be extracted and the type of citrus fruits treated. The yield of the extracted compound is also affected by the solvent used, and the operation duration, temperature, pH and the ratio of solute to solvent.

5.1 | Pectins

Pectin is a gelatinous polysaccharide with a high molecular weight that is found in the citrus cell wall and middle lamella. It binds the plant cells to provide the plant with strength and flexibility. It comprises of a linear chain of D-galacturonic acid units linked together by α-1,4 glycosidic linkages, which are partially esterified at the carboxylic acid using methanol or acetic acid to produce methyl esters. Citrus wastes contain a high proportion of pectin (20%–30%) in the overall dry weight of peels compared with those of apples by-products (10%–15%). In citrus wastes, there are two types of pectins: insoluble pectins and soluble pectins, which range in colour from white to light brown. Pectins are used in food manufacture as a thickening, emulsifying, texturizing or stabilizing agent and as a fat substitute. Pectins can be used in the processing of jams, jellies, bakery fillings, confectionary products and biodegradable films (Min et al., 2010; Satari et al., 2017).

5.2 | Phenolic substances

Citrus wastes have higher levels of polyphenols ranging from 0.67% to 19.62% on dry basis when compared with the edible portion of the fruit (M'hiri et al., 2017). As a result, they have a variety of health-related characteristics, including antioxidant, anti-inflammatory, anticancer, and antibacterial activities. The polyphenol composition varies depending on the type of citrus by-products. Gallic acid, ferulic acid, chlorogenic acid, hesperidin, rutin and naringenin are all found in lemon (*C. limon*) peels, whereas caffeic acid and eriocitrin are found in its seeds. The main flavanones found in bergamot, lemon and orange peels are neoeriocitrin, naringin and neohesperidin. On the contrary, the most abundant flavonoids in sweet orange are hesperidin and narirutin.

The most abundant polyphenols in the peels or flavedo are flavonoids. They include four groups, flavanones present in high

TABLE 2 Concentration of bioactive compounds in citrus by-products, peel, pulp and juice

Bioactive compounds	Peel	Pulp	Juice	Sources and references
Total phenolics ($\mu g\, ml^{-1}$)	147.6	57.7	673.9	Rapisarda et al. (1999); Goulas and Manganaris (2012)
Total flavonoids ($\mu g\, ml^{-1}$)	49.2	1.15	260.1	Rapisarda et al. (1999); Wang et al. (2008); Goulas and Manganaris (2012)
Antioxidant activity	656.18	456.7	46.35	Goulas and Manganaris (2012)
Total carotenoids ($\mu g\, g\, DW^{-1}$)	2.04	–	–	Wang et al. (2008)

quantities followed by flavones (luteolin, apigenin and diosmin), flavonols, isoflavones, flavanols and anthocyanins. Dry citrus peels contain 2%–3% flavanone and 0.91%–4.92% of total polyphenols. They have a protective role against Alzheimer's and Parkinson's diseases as they elicit a strong antioxidant impact and lipid peroxidation inhibition (Mulvihill & Huff, 2012; Wang et al., 2014).

The peels also contain phenolic acids, including hydroxybenzoic (gallic, vanillic and syringic acids) and hydroxycinnamic acids (caffeic, ferulic, p-coumaric and sinapic acids). They have a potent antioxidant effect as these substances act as free radical scavengers and heavy metals chelating agents. Peroxides such as reactive oxygen species, superoxide radical, hydrogen peroxide, hypochlorous acid and hydroxyl radical initiate oxidation and auto-oxidation of lipid in the food, which then cause fat rancidity and breakdown. This indeed negatively change the nutritional value and physical properties of the food (i.e. colour, flavour, odour and texture) especially those of high-fat content, such as in meat products. Also, peroxides can decrease the shelf half-life of food. They have toxic effects on human health, through the peroxidation of the phospholipids of the cell membranes found in different body cells and organs (resulting in cell ageing). This, in turn, will cause serious health problems, such as cancer, diabetes, nervous and cardiac diseases (Aruoma, 2003; Hool, 2006; Huang et al., 2001; Perry et al., 2000).

There are synthetic antioxidants such as butylated hydroxyanisole (BHA), butylated hydroxytoluene and natural antioxidants. Synthetic antioxidants are used to restore the food nutrient quality from oxidation. It has been reported that BHA helps in the growth of cancer cells in the rat. Therefore, it is necessary to extract natural antioxidants from food by-products to resolve the adverse effects of synthetic antioxidants (Burlow, 1994; Moure et al., 2001). Orange (*C. sinensis* L. and *Citrus aurantium* L.) by-products and phenolic acids isolated from kinnow rind powder have been used as natural antioxidants (Benamrouchea & Madania, 2013; Devatkal et al., 2010). Also, 40-geranyloxyferulic and boropinic acids are found to be abundant in *C. sinensis* while kumquats possess antibacterial properties (Genovese et al., 2014).

5.3 | Carotenoids

Carotenoids are natural pigments synthesized by plants, algae, some bacteria and fungi. They are the most common type of isoprenoids and responsible for colours found in fruits and vegetables. Citrus wastes contain two types of carotenoids: oxygenated xanthophylls such as lutein and violaxanthin, and hydrocarbon carotenoids such as carotene and lycopene. There are approximately 115 carotenoids in citrus fruits, which give them their appealing colours (Namitha & Negi, 2010). Carotenoids are characterized by their high antioxidant and provitamin A functions. Also, they may be used as colouring agents in food and beverage preparation. Carotenoid extraction is difficult due to the presence of rigid cell walls in citrus wastes. Hence, before the extraction procedure, citrus wastes must be cooked, dried, frozen and treated with enzymes (Zou et al., 2016).

5.4 | Limonoids

Citrus wastes contain limonoids, which include limonoid aglycones (e.g. limonin and nomilin) and limonoid glucosides (e.g. limonin glucoside and nomilic acid glucoside). The limonoid aglycones, which are present predominantly in citrus seed or peels, are insoluble in water and induce the bitter flavour of citrus fruits and juices. Limonoid glucosyltransferase transforms limonoids into tasteless limonoids during maturation, which decreases the bitterness of citrus fruits (Qin et al., 2018).

Citrus juice and pulp include limonoid glucosides, which are water soluble. Citrus liquids develop a delayed bitterness over time, lowering the quality and acceptability of the fruit juice. To increase the quality and acceptability of citrus juice, physical, chemical and microbiological approaches have been investigated (Bi et al., 2019; Breksa et al., 2009; Manners, 2007).

Limonoids have antibacterial, antioxidant, anticancer and cholesterol-lowering properties. Compared with any other by-product of citrus, citrus molasses contains the highest concentration of limonoids. Furthermore, the viscous liquid shape of molasses makes it the most promising source for limonoids recovery (Hasegawa & Miyake, 1996; Russo et al., 2016).

5.5 | Essential oils

At 0.6% and 3.8% dry basis, citrus essential oils (CEO) are aromatic liquids comprising mixtures of 20–60 different types of volatile compounds found in the oil sacs situated in the depths of citrus peels

(M'hiri et al., 2016). CEO are lipophilic compounds with low water solubility and are fluid at room temperature. CEO comprise primarily of isoprenoids and terpene carbohydrate derivatives (i.e. monoterpenes and sesquiterpenes), alkenses, acids, alcohols, ketones, aldehydes, esters, phenols and nitrogen compounds. Limonene constitutes up to 90%–98% of CEO. These compounds are used in the dairy, medical, medicinal and cosmetic industries as flavouring agents. CEO have antibacterial, antioxidant and biocidal effects against fungi, viruses, protozoa, insects and plants (Negro et al., 2016; Schieber et al., 2001). Essential oils derived from citrus peel wastes have been examined for their antibacterial and antifungal properties (Afzalani Zein et al., 2015; Callaway et al., 2011a, 2011b; Nam et al., 2006).

5.6 | Dietary fibres

Citrus fruits are high in soluble dietary fibres (SDF) and insoluble dietary fibres (IDF) that are mostly concentrated in the peel. Gums, pectins, glucans and a variety of biological and synthetic polysaccharides are examples of SDF, whereas cellulose, hemicellulose and lignin are examples of IDF. Furthermore, citrus waste fibres have a high nutritional value, a well-balanced composition and are high in SDF and bioactive elements including flavonoids and carotenoids.

Gorinstein et al. (2001) found that lemon peels and peeled fruits have the highest antioxidant activity when compared with oranges and grapefruits. For lemon and orange peels, the fibre content is 14 g/100 g in dry matter (DM) and 57 g/100 g DM respectively (Fishman et al., 1999). The cellulose and hemicellulose contents of citrus peel can range from 50% to 60%. Pectins, lignins, celluloses and hemicellulose of lemon and orange peels range are as follows: 13.00–23.03 g/100 g DM, 7.52–7.56 g/100 g DM, 23.06–37.08 g/100 g DM and 8.09–11.04 g/100 g DM respectively (Marín et al., 2007). Citrus fibres, which contain polysaccharides and polyphenol-like components, have antioxidant qualities that inhibit lipid oxidation in meat products, maintain oxidative stability and extend the shelf life of meats. Orange juice fibre has also been utilized as a fat substitute in ice cream and the meat industry due to its ability to retain water and oil (de Moraes Crizel et al., 2013; Fernández-Ginés et al., 2003; Mehta et al., 2015; Sáyago-Ayerdi et al., 2009).

6 | EFFECTS OF SUPLEMENTAL CITRUS WASTE PRODUCTS AND EXCTRACTS ON FISH GROWTH

Several studies have recently been carried out to assess the impact of citrus waste products (CWP) on the growth performance of several fish species (Table 3). Supplementing diets with lemon peel (*Citrus auranitiifolia*) or bergamot (*C. bergamia*) peel oil enhanced the growth performance of Nile tilapia (*Oreochromus niloticus*) and European sea bassf (*Dicentrarchus labrax*) respectively (Acar et al., 2019; Toutou et al., 2018). The antibacterial and antioxidant characteristics of dietary lemon peel may explain the better growth performance and food conversion efficiency of fish given various doses of the peel (Milos et al., 2000). Additionally, lemon peel might be used to supplement fish feed with a low-cost supply of vitamin C. Furthermore, bergamot essential oils are also a good source of bioavailable substances, such as, limonene, linalool, linalyl acetate and β-pinene (Costa et al., 2010). In the same context, the addition of grapefruit (*Citrus paradise*) peel extract to Caspian white fish (*Rutilus frisii kutum*) diets at different levels (0, 6.25, 12.5 and 25 mg kg^{-1} diet) increased fish growth performance (Samavat et al., 2019). This is most likely linked to the increased nutritional digestion and absorption capabilities of the fish as a result of the healthy gut microbiota (MacLennan et al., 2002). Furthermore, it is well known that the inclusion of plant products or plant-based bioactive compounds to fish feeds improves the digestive system of the fish. In particular, supplementations improved the absorption surface in the digestive tract, leading to greater nutritional absorption and growth (Demirci et al., 2021). It has been noted that the digestive system of tilapia fed feeds containing D-limonene-rich lemon and orange essential oils was strengthened, resulting in increased growth performance (Mohamed et al., 2021). Gültepe (2020) found that adding D-limonene obtained from sweet orange (*C. sinensis*) peel to rainbow trout diets at concentrations of 0.5, 1 and 3 ml kg^{-1} improved fish growth performance. Moreover, the inclusion of essential oils extracted from orange (*C. aurantium*) peel at 0.25, 0.5, 1.0 and 2.0 ml kg^{-1} in silver catfish (*Rhamdia quelen*) diets improved the production performance and antioxidant capacity (Lopes et al., 2019). Also, there was a significant improvement in growth of Nile tilapia fed diets supplemented with essential oils extract from sweet orange (*C. sinensis*) and/or lemon (*C. limon*) peels (Mohamed et al., 2021). Moreover, increased dietary levels of lemon essential oil loaded in chitosan nanoparticles increased growth indices and feed utilization of rainbow trout, *Oncorhynchus mykiss* (Gheytasi et al., 2021). The addition of 0.25% of the essential oil (Neroli oil) derived from bitter orange (*C. aurantium*) to the diets improved the growth of common carp (*Cyprinus carpio*) (Acar et al., 2021). These may be attributed to the quick absorption of essential oils in the gastrointestinal tract of fish (Gültepe, 2018). There was also an improvement in the growth performance and feed utilization of Siberian sturgeon (*Acipenser baerii*) fed lemon verbena (LV) (*Aloysia citrodora*) extract at the rate of 10–20 mg kg^{-1} (Adel et al., 2021). Dietary LV is high in phytochemicals and aromatic tastes, which improve diet palatability and feed ingestion and utilization (Bahramsoltani et al., 2018). Also, the LV protects the intestinal epithelial layer resulting in increased mucus secretion and improved passage of the digested nutrients through villi until they reach the circulation; these lead to the improvement of the growth performance (Zhu, 2020). In addition, ingested nutrients contribute to many metabolic roles necessary for important processes, resulting in improved growth performance (Dawood et al., 2021). Furthermore, the polyphenols in LV have an antibacterial impact, allowing good bacteria to breakdown nutrients via released digestive enzymes (Furné et al., 2005). On the contrary, the study of Abdel Rahman et al. (2019) found non-significant reduction in growth of Nile tilapia (*O. niloticus*) fed 1% and 2% dried lemon peel *C. limon*

TABLE 3 Biological activities of citrus wastes and essential oils thereof when used for diets of different fish species

Citrus species and products	Fish species	Dosage level	Effects and benefits	Sources and references
Dehydrated lemon peel powder	Gilthead seabream (*Sparus aurata* L.)	1.5% and 3%	↑ Growth ↑ Expression of some immune-related genes: antioxidant gene *nkefa*, pro-inflammatory gene *il1b*, antibody *igth* and macrophage stimulator gene *csfr1*	Beltrán et al. (2017)
Dehydrated lemon peel powder	Nile tilapia (*Oreochromis niloticus*)	1% and 2%	↑ Serum glucose ↑catalase (CAT), superoxide dismutase (SOD), glutathione (GSH) ↑ Serum lysozyme activity (LYZ), myeloperoxidase activity (MPA) ↔ Serum cortisol (COR) ↓ Growth	Abdel Rahman et al. (2019)
Dehydrated lemon peel powder	African catfish (*Clarias gariepinus*)	1% and 2%	↑ CAT, SOD, GSH ↑ Serum LYZ, MPA ↔ Growth ↔ Serum glucose (GLU) ↔ Serum COR	Abdel Rahman et al. (2019)
Lemon (*C. aurantiifolia*) peel	Nile tilapia (*O. niloticus*)	0.5%, 1%, and 2%	↑ Growth ↓ Serum GLU	Toutou et al. (2018)
Lemon (*C. aurantiifolia*) peel	Thin-lip mullet (*Liza ramada*)	0.5%, 1%, and 2%	↑ Growth ↓ Serum GLU	Toutou et al. (2018)
Bergamot (*C. bergamia*) peel oil	Nile tilapia (*O. niloticus*)	0.5%, 1.0%, and 2.0%	↑ Growth ↑ Red blood cells (RBC), hematocrit (HCT), haemoglobin (Hb) ↑ Serum total protein (TPRO) ↓ Serum glucose ↓ Serum cholesterol (CHO), triglyceride (TRI) ↓ Glumatic oxaloacetic transaminase (GOT), glumatic pyruvic transaminase (GPT), alkaline phosphatase (ALP) and lactate dehydrogenase	Kesbiç et al. (2020)
C. aurantium essential oil	Silver catfish (*Rhamdia quelen*)	0.25, 0.5, 1.0, and 2.0 ml kg^{-1} diet	↑ Growth ↑ GLU, lactate (LAC), and protein levels in liver and muscle ↑ SOD activity in liver ↑ Growth hormone ↔ Prolactin, somatolactin ↓ Thiobarbituric acid reactive substance and lipid hydroperoxides ↓ Glutathione S-transferase activity in liver	Lopes et al. (2019)
Dehydrated lemon peel	Gilthead seabream (*S. aurata* L.)	1.5% and 3%	↑ Growth ↑ Serum GLU, urea, total antioxidant status, alanine transaminase (ALT), LAC ↑ Oxidative stress and apoptosis: Hsp 70, Hsp 25 and Phospho-c-jun in skin mucus ↑ Serum TPRO ↑ Serum SOD, CAT, GPX and LYZ	Beltrán et al. (2017)
Bergamot (*C.bergamia*) peel oil	European sea bass (*Dicentrarchus labrax*)	0.5%, 1.0%, and 2.0%	↔RBC, HCT and Hb ↓ Serum GLU, ALP, GOT, CHO	Acar et al. (2019)

(Continues)

TABLE 3 (Continued)

Citrus species and products	Fish species	Dosage level	Effects and benefits	Sources and references
Citrus × latifolia essential oil	Tambaqui (*Colossoma macropomum*)	0.25, 0.5, 1.0, and 2.0 ml essential oil kg^{-1} diet	↑ Lipid peroxidation in muscle ↑ Reactive oxygen species (ROS) in liver ↑ SOD in liver ↔ SOD in muscle ↔ GPX in liver and muscle ↓ ROS in muscle	Lopes et al. (2020)
Dried lemon (*Citrus lemon*) pomace	Common carp (*Cyprinus carpio*)	1.5%, 3%, and 5%	↑ Growth ↑ RBC, GSH, GPX, SOD ↑ Plasma ferric reducing antioxidant power (FRAP) ↔ Plasma ALT, aspartate aminotransferase (AST), ALP, TPRO, albumin (ALB), bilirubin, urea ↓ Plasma malondialdehyde (MDA)	Laein et al. (2021)
Bitter lemon (*C. limon*) peels	Nile tilapia (*O.niloticus*)	0.75% and 1%	↑ Growth ↑ LYZ, phagocytic activity, total leucocytes ↑ SOD and CAT ↑ Somatotropic axis growth-mediation gene *igf-I*, antioxidant enzyme activity gene *sod*, and immune-related pro-inflammatory cytokine gene *tnf-α* expression in liver ↔ RBC, Hb, packed cell volume (PCV), TPRO, and ALB ↔ Lymphocytes, heterophils, monocytes ↓ GLU, globulin (GLO), CHO, TRI, ALT, AST	Mohamed et al. (2020)
Grapefruit (*C.paradisi*) peel extract	Caspian white fish (*Rutilus frisii kutum*)	6.25, 12.5, and 25 mg peel extract kg^{-1}	↑ Growth ↑ RBC, white blood cells (WBC), PCV and Hb ↑ SOD ↓ GLU, CHO, AST, ALP, and ALT	Samavat et al. (2019)
Dried lemon (*C. limon*) peel	Rohu (*Labeo rohita*)	1, 2.5, and 5 g kg^{-1}	↑ Growth ↑ WBC, TPRO, ALB, and GLO ↑ SOD, CAT, GPX, MDA and GSH ↑ Phagocytic activity, respiratory burst activity, peroxidase activity, alternative complement pathway, serum complement C3 level, LYZ, serum total immunoglobulin M (IgM) ↑ Hsp 70 and Hsp 90, SOD, glutathione peroxidase, glutathione, interleukin-1β and interleukin-8, tumour necrosis factor alpha, inducible nitric oxide synthase, transforming growth factor beta, and IgM	Harikrishnan et al. (2020)
Lemon (C. *aurantifolia*) peel	Common carp (*C. carpio*)	1.5% and 3%	↑ Growth ↑ WBC, TPRO, ALB ↑ Serum LYZ ↑ CAT, SOD, GPX ↔ RBC, HCT, Hb, lymphocyte and neutrophil ↔ CHO, TRI, GLO, AST, ALT, and ALP ↓ MDA	Sadeghi et al. (2021)

TABLE 3 (Continued)

Citrus species and products	Fish species	Dosage level	Effects and benefits	Sources and references
Citrus limon peel	Ningu (*Labeo victorianus*) fingerlings	10, 20, 50 and 80 g kg^{-1}	↑ Growth, ↑ ALB, RBC, WBC, HCT, Hb, TPRO, mean corpuscular volume (MCV), mean corpuscular haemoglobin (MCH), mean corpuscular haemoglobin concentration (MCHC), serum Ig, LYZ, respiratory burst activity ↓ Plasma COR, GLU, TRI, CHO, lymphocytes, neutrophiles	Ngugi et al. (2017)
Limonene by citrus peel origin	Nile tilapia (*O. niloticus*) fingerlings	200, 400, and 600 ppm	↑ Growth ↑ Gene expression levels of insulin growth factor I *igf-I*, alkaline phosphatase *alp*, lipoprotein lipase *lpl*, oligo-peptide transporter 1 *pept1*, mucin-like protein *muc*, catalase *cat*	Aanyu et al. (2018)
C. sinensis fragment	Nile tilapia (*O. niloticus*) (31 g)	0.2%, 0.4%, 0.6%, and 0.8%	↑ Lymphocyte, neutrophil, monocyte ↔ Growth ↔ RBC, Hb, HCT, MCV, MCHC, TPRO, ALB, GLO, CAT ↓ SOD, GPX	Vicente et al. (2019)
Dehydrated *C. sinensis* peel powder	Catla (*Catla catla*)	2, 6, and 10 g kg^{-1}	↑ Growth ↑ Fillet quality, fillet amino acid amount, digestive system protease, amylase, lipase ↔ Serum GOT, GPT, fillet fatty acid amount	Shabana et al. (2019)
Dehydrated (*C. sinensis*) peel powder	Common carp (*C. carpio*)	1, 3 and 5 g kg^{-1}	↑ Growth	Allah Beygi et al. (2019)
Lemon (*C. lemon*) peel and pulp powder	Common carp (*C. carpio*)	1.5%, 3%, and 5%	↑ Growth ↑ MDA, FRAP ↓ Protein carbonyl contents	Safaeian Laein et al. (2018)
C. sinensis peel	Rainbow trout (*Oncorhynchus mykiss*)	0.5, 1, and 3 g kg^{-1}	↑ Growth	Gültepe (2018)
Lemon (*C. aurantiifolia*) peel powder	Nile tilapia (*O. niloticus*)	0.5%, 1% and 2%	↑ Growth ↑ Fillet quality, creatinine (CRE) ↔ Lipase (LIP) ↓ CHO, TRI, amylase (AMY), GLU	Toutou et al. (2018)
Lemon (*C. aurantiifolia*) peel powder	Thin-lip mullet (*L. ramada*)	0.5%, 1% and 2%	↑ Growth ↑ Survival rate, fillet quality, CRE, CHO, TRI, LIP ↓ AMY, GLU	Toutou et al. (2018)
C. sinensis fragment	Nile tilapia (*O. niloticus*)	1, 2, and 4 g kg^{-1}	↑ Growth ↑ fillet quality, digestive system surface area	Salem and Abdel-Ghany (2018)
Dehydrated lemon (*C. limon*) peel	Rainbow trout (*O. mykiss*)	0.5%, 1.5%, and 2.5%	↑ Growth After crowding stress: ↑ Serum CAT, SOD, MDA, GPX, Total Ig, IgM, LYZ, alternative complement	Chekani et al. (2021)

diets and in African catfish (*Clarias gariepinus*) fed 2% *C. limon* diet. Similarly, there was a significant decrease in growth efficiency of gilthead sea bream (*Sparus aurata*) using 3% dehydrated lemon peel (DLP) in diets for 30 days (Beltrán et al., 2017). One explanation for the observed decrease in fish development might be connected to lemon's diuretic properties in mammals, which means it promotes urine output in the kidneys and thus aids in the elimination of excess fluid (Menichini et al., 2015; Wu et al., 2015). Another explanation might be connected to the antilipogenesis action of lemon and the genus *Citrus* in *in vivo* studies in rats and in *in vitro* studies (Menichini et al., 2015; Miyake et al., 2006). New studies may assist to figure out why these outcomes are happening, and show if DLP has diuretic or antilipogenesis properties in fish.

7 | EFFECTS OF CWP AND EXTRACTS ON HEMATO-BIOCHEMICAL INDICES

Haematological, serum biochemical and immunological parameters, antioxidant enzyme activities and gene expressions have been well-documented to determine the effects of citrus by-products supplementation in fish feeds used for in vitro feeding experiments (Table 3). The addition of essential oil extracted from *C. limon* peel up to 5% in diet was enhanced the biochemical, haematological and immunological responses in cyprinid fish *Labeo victorianus* fingerlings (Ngugi et al., 2017). Moreover, Samavat et al. (2019) observed that adding grapefruit (*C. paradise*) peel extract (GFE) at a level of 25 mg kg^{-1} markedly enhanced the hemato-biochemical indices including red blood cell (RBC) and white blood cell (WBC) counts, packed cell volume and haemoglobin (Hb) values of Caspian white fish (*R. frisii kutum*). As a result, it is possible that GPE activates the hematopoietic tissue of the fish. However, further research works are required to illustrate the mode of action.

On the contrary, supplemental diets with *C. auranitiifolia* peel and *C. sinensis* fragment did not induce any marked effects on the haematological parameters of common carp (*C. carpio*) and Nile tilapia (Mohamed et al., 2021; Sadeghi et al., 2021). Also, orange essential oil and/or lemon essential oil had no marked effects on the haematological indices including Hb and RBC of the cultured fish (Acar et al., 2019; Vicente et al., 2019). Blood parameters may differ between species, and even within fish of the same species, depending on a variety of factors, such as water quality, sampling method and feeding (Gallaugher & Farrell, 1998). Despite these variables, CWP utilization in fish feeds for various cultured species has been found to have no deleterious impacts on fish haematological parameters. Using bitter lemon (*C. lemon*) peel at 0.75% and 1% levels decreased serum glucose, globulin, cholesterol, triglycerides, alanine transaminase and aspartate aminotransferase values of Nile tilapia (Mohamed et al., 2021). Similarly, Toutou et al. (2018) reported that the serum glucose level of Nile tilapia and thin-lip mullet (*Liza ramada*) fed diets supplemented with *C. aurantiifolia* peel was dramatically reduced when fed at 0.5%, 1% and 2% levels because stress was avoided under high levels of (vitamin C) lemon peel. Also, serum glucose, cholesterol, alkaline phosphatase and aspartate aminotransferase values were decreased using bergamot (*C. bergamia*) peel oil (BPO) up to 1% in European seabass (*D. labrax*) diets due to the presence of limonene, which is a key component of BPO that has a protective effect on the liver health status of sea bass (Acar et al., 2019). While, adding lemon verbena (*A. citrodora*) extract was increased the RBC, WBC, Hb, hematocrit and total protein contents of Siberian sturgeon (*A. baerii*; Adel et al., 2021). This increase might be attributed to the availability of vitamin C, amino acids and natural immunostimulants in the lemon verbena extract, which benefit the general health of the Siberian sturgeon (Bahramsoltani et al., 2018). In line with the previous studies, the serum glucose and cholesterol levels were lowest in Mozambique tilapia (*O. mossambicus*) and rainbow trout fed diets containing sweet orange (*C. sinensis*) essential oil and lemon essential oil loaded in chitosan nanoparticles (Acar et al., 2015; Gheytasi et al., 2021). The potential of plant oils to mitigate the impacts of stressors in fish farming might explain the decrease in glucose concentrations (Güleç et al., 2013). Indeed, polymethoxylated flavones and hesperetin (a flavanone derivative) compounds found in lemon essential oil decrease cholesterol and triglyceride biosynthesis (Baba et al., 2016; Kurowska & Manthey, 2004; Ngugi et al., 2017).

8 | EFFECTS OF CWP AND EXTRACTS ON IMMUNE RESPONSE

The study of phagocytic activities, phagocytic indices, lysozyme activities, WBC and differential WBC counts are standard tools to assess the immunological responses of fish (Hassaan et al., 2019, 2020, 2021; Mohammady et al., 2021). In fish, phagocytosis is an important part of cell-mediated immunity. It detects the pathogen, inhibits its transmission and thereby lowers disease outbreaks (Kawahara et al., 1991). Lysozyme activity is a crucial defence mechanism that causes lysis of pathogenic bacteria (Saurabh & Sahoo, 2008). The immunological response of Nile tilapia including lysozyme activity, phagocytic activity and phagocytic index was improved by adding essential oil extracted from lemon at 3% and/or sweet orange peels at 0.75% (Mohamed et al., 2021). Furthermore, the dietary administration of oregano essential oils (OES) extracted from *Origanum vulgare* at a concentration of 15 g kg^{-1} improved these immunological parameters in common carp (*C. carpio*) (Abdel-Latif et al., 2020) due to the probable function of the primary components of OES and thymol and carvacrol in enhancing fish disease defence (Saurabh & Sahoo, 2008; Sivropoulou et al., 1996). Moreover, there was an improvement in the lysozyme activity of Mozambique tilapia (*O. mossambicus*) by adding essential oils extracted from lemon and orange peels (*C. sinensis*) (Acar et al., 2015; Baba et al., 2016). Indeed, increasing the amount of lemon essential oil loaded with chitosan nanoparticles in rainbow trout (*O. mykiss*) diets steadily increased serum lysozyme activity (Gheytasi et al., 2021).

9 | THE INFLUENCE OF CWP AND EXTRACTS ON ANTIOXIDANT ACTIVITY

Catalase (CAT) and superoxide dismutase (SOD) are essential enzymes in modulating and relieving antioxidant mechanisms and cellular immunity in fish (Al-Deriny et al., 2020). However, there was an increase in the activities of SOD and CAT in Nile tilapia fed essential oils extracted from sweet orange (*C. sinensis*) and/or lemon (*C. limon*) peels, indicating the enhancement in fish resistance against any oxidative stress (Mohamed et al., 2021). The study on the effects of bergamot (*C. bergamia*) peel oil on European sea bass (*D. labrax*) showed a similar pattern on the increase in SOD and CAT levels (Acar et al., 2019). This increase in SOD could maintain the level of superoxide anion or it may facilitate the process of conversion to O_2 or OH^- through metal facilitate interaction to improve the microbial exterminate potential of phagocytes (Yilmaz, 2019a, 2019b).

In Nile tilapia and African catfish fed *C. limon* peels (1% and 2%), Abdel Rahman et al. (2019) found a considerable increase in the activities of CAT and SOD enzymes, except for SOD in Nile tilapia, which remained unaltered. Additionally, after feeding a mixture of *Bacillus licheniformis* and lemon peel powder to common carp, serum SOD, CAT and glutathione peroxidase (GPX) levels were increased (Sadeghi et al., 2021). Rohu (*Labeo rohita*) fed with 2.5 and 5 g kg^{-1} dried lemon peel diets markedly regulated SOD, CAT and GPX while malondialdehyde did not change in any of the treatments according to Harikrishnan et al. (2020).

10 | EFFECTS OF CWP AND EXTRACTS ON GENE EXPRESSION

Several studies have revealed the influence of various forms of bioactive compounds derived from plant sources on growth performance and blood metabolites in fish, but information about the pathways in which the changes occur is still lacking. Therefore, the measurement of the level of gene expression may help in elucidating the growth and/or metabolic differences.

Limonene obtained from orange peel had effects on growth (growth hormone, growth hormone receptor I and insulin growth factor I), feed utilization (mucin-like protein, oligo peptide transporter 1, alkaline phosphatase, chymotrypsinogen A-like, phospholipase, glucose transporter 2, aminopeptodase N-like and pancreatic alpha-amylase), lipid metabolism (lipoprotein lipase, peroxisome proliferator-activated receptor alpha, sterol regulatory element binding transcription factor 1 and fatty acid synthase) and oxidative stress (GPX, CAT, and SOD2) associated with gene expression levels of Nile tilapia *O. niloticus* (Aanyu et al., 2018).

Dehydrated citrus peel is another form of citrus wastes that has been utilized as an aquafeed. Rohu (*L. rohita*) fed diets supplemented with dehydrated lemon peel at 2.5% and 5% levels have exhibited improved expression levels of immuno-antioxidant genes such as heat-shock proteins 70 and 90, SOD, GPX, interleukins 1β and 8, tumour necrosis factor alpha, inducible nitric oxide synthase, transforming growth factor beta, immunoglobulin M and hepcidin (Harikrishnan et al., 2020). Moreover, Nile tilapia fed with essential oils extract from sweet orange (*C. sinensis*) and/or lemon (*C. limon*) peels showed increased somatotropic axis growth-mediation gene, antioxidant enzyme activity gene (SOD) and immune-related pro-inflammatory cytokine gene expressions (Mohamed et al., 2021). In common carp (*C. carpio*), dietary supplementation of oregano essential oil (15 g kg^{-1}) elevated the relative expression of hepatic interleukin-1beta (IL-1β) and interleukin-10 (IL-10) genes (Abdel-Latif et al., 2020). In general, using immunostimulants in common carp diets can boost IL-1 and IL-10 expression (Hoseinifar et al., 2017; Watanuki et al., 2006).

11 | IN VITRO STUDIES RELATING TO FISH PATHOGENS

Studies on the use of CWP for in vivo aquaculture applications have been limited. Generally, citrus peel products, particularly essential oils, have antibacterial properties against various pathogens. Citrus products, particularly the essential oils produced from citrus peel, have been demonstrated to be prospective products that can be employed against bacterial fish pathogens in studies using citrus products against pathogens isolated from fish. D-limonene, the primary component of citrus peel essential oil and lime peel essential oil, has been evaluated as a viable alternative to antibiotics in an in vitro experiment of pathogens identified from flounder, one of the most important aquaculture species (Pathirana et al., 2018). Citrus peel essential oils have been shown in experiments to exhibit an antibacterial impact on various of fish infections. As a result, Mancuso et al. (2019) suggested that *Vibrio* sp. and *Photobacterium* sp., which cause serious losses in aquaculture systems, are sensitive to essential oils and can be utilized to fight fish infections. In vitro studies have mainly covered the use of citrus essential oils, which have shown to exhibit antibacterial activity against different fish infections (Table 4).

12 | CONCLUSION

Waste products are becoming more prevalent in today's society and can constitute a significant health and environmental concern. Therefore, this paper contains a review of the current research on the utilization of citrus wastes in different aquaculture-related studies. Although a number of studies have already been published on the use of citrus wastes (especially the peel or flavedo) in aquafeeds, while it was in fact quite a more recent undertaking. Every

TABLE 4 Antimicrobial effects of *Citrus sinensis* peel essential oils against fish pathogens

Fish pathogens	Sources and references
Klebsiella pneumoniae, Yersinia enterocolitica, Klebsiella pneumoniae, Staphylococcus aureus, Staphylococcus aureus, Listeria monocytogenes, Bacillus subtilis, Yersinia enterocolitica, Staphylococcus aureus, Yersinia ruckeri, Aeromonas hydrophila, Lactococcus garvieae, Listonella anguillarum, Edwarsiella tarda, Citrobacter freundii	Ozogul et al. (2015); Debbarma et al. (2013); Öntaş et al. (2016)

year, various citrus products, primarily orange juice and lemonade, are manufactured and marketed as raw materials. Citrus residues, which would otherwise be dumped as trash in the environment, should be considered as prospective nutraceutical resources capable of providing low-cost nutritious dietary supplements due to their cheap cost, accessibility and availability. These undesired industrial cast-offs, which are rich in bioactive components, might be valuably recycled into value-added functional food supplements that provide beneficial dietary fibre and polyphenols with potential prospectives for preventive therapies for some diseases. They act as non-caloric bulking agents, increase water and oil retention, improve emulsion and may protect from oxidative stress-related disorders. Fruit peel extracts have potential as bioactive chemical sources in the food industry. Furthermore, a well-established citrus peel utilization would aid in the reduction in pollution caused by improper disposal of such wastes. Thus, finding novel uses for these waste materials not only contributes to environmental protection but also for tapping in potential economic gains from converting low-value wastes into high-value and marketable products. Aquaculture is one of the ideal industries that could benefit from the use of products and extracts obtained from citrus wastes. In addition, further research (in vitro and in vivo) is needed to determine the bioavailability and practical advantages of using citrus peel extracts.

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CONFLICT OF INTEREST

The authors declare that they have no competing interest.

AUTHORS CONTRIBUTIONS

The authors state that their individual contribution is equal.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Aanyu, M., Betancor, M. B., & Monroig, O. (2018). Effects of dietary limonene and thymol on the growth and nutritional physiology of Nile tilapia (*Oreochromis niloticus*). *Aquaculture*, *488*, 217–226.

Abdel Rahman, A. N., El Hady, M., Shimaa, I., & Shalaby, S. H. I. (2019). Efficacy of the dehydrated lemon peels on the immunity, enzymatic antioxidant capacity and growth of Nile tilapia (*Oreochromis niloticus*) and African catfish (*Clarias gariepinus*). *Aquaculture*, *505*, 92–97.

Abdel-Latif, H. M., Abdel-Tawwab, M., Khafaga, A. F., & Dawood, M. A. (2020). Dietary oregano essential oil improved antioxidative status, immune-related genes, and resistance of common carp (*Cyprinus carpio* L.) to *Aeromonas hydrophila* infection. *Fish & Shellfish Immunology*, *104*, 1–7.

Acar, Ü., Kesbiç, O. K., Yılmaz, S., İnanan, B. E., Zemheri-Navruz, F., Terzi, F., Fazio, F., & Parrino, V. (2021). Effects of essential oil derived from the bitter orange (*Citrus aurantium*) on growth performance, histology and gene expression levels in common carp juveniles (*Cyprinus carpio*). *Animals*, *11*(5), 1431. https://doi.org/10.3390/ani11051431

Acar, Ü., Kesbiç, O. S., İnanan, B. E., & Yılmaz, S. (2019). Effects of dietary Bergamot (*Citrus bergamia*) peel oil on growth, haematology and immune response of European sea bass (*Dicentrarchus labrax*) juveniles. *Aquaculture Research*, *50*(11), 3305–3312.

Acar, Ü., Kesbiç, O. S., Yılmaz, S., Gültepe, N., & Türker, A. (2015). Evaluation of the effects of essential oil extracted from sweet orange peel (*Citrus sinensis*) on growth rate of tilapia (*Oreochromis mossambicus*) and possible disease resistance against *Streptococcus iniae*. *Aquaculture*, *437*, 282–286.

Adel, M., Dawood, M. A. O., Gholamhosseini, A., Sakhaie, F., & Banaee, M. (2021). Effect of the extract of lemon verbena (*Aloysia citrodora*) on the growth performance, digestive enzyme activities, and immune-related genes in Siberian sturgeon (*Acipenser baerii*). *Aquaculture*, *541*, 736797.

Afzalani Zein, M., Jamarun, N., & Musnandar, E. (2015). Effect of increasing doses of EO extracted from berastagi orange peels on performance, rumen fermentation and blood metabolites in fattening Bali cattle. *Pakistan Journal of Nutrition*, *14*, 480–486.

Al-Deriny, S. H., Dawood, M., Zaid, A., El-Tras, W., Paray, B. A., Van Doan, H., & Mohamed, R. (2020). The synergistic effects of *Spirulina platensis* and *Bacillus amyloliquefaciens* on the growth performance, intestinal histomorphology, and immune response of Nile tilapia (*Oreochromis niloticus*). *Aquaculture Reports*, *17*, 100390. https://doi.org/10.1016/j.aqrep.2020.100390

Aruoma, O. I. (2003). Methodological considerations for characterizing potential antioxidant actions of bioactive components in plant foods. *Mutation Research*, *523-524*, 9–20. https://doi.org/10.1016/s0027-5107(02)00317-2

Baba, E., Acar, Ü., Öntaş, C., Kesbiç, O. S., & Yılmaz, S. (2016). Evaluation of *Citrus limon* peels essential oil on growth performance, immune response of Mozambique tilapia, *Oreochromis mossambicus* challenged with *Edwardsiella tarda*. *Aquaculture*, *465*, 13–18.

Bahramsoltani, R., Rostamiasrabadi, P., Shahpiri, Z., Marques, A. M., Rahimi, R., & Farzaei, M. H. (2018). *Aloysia citrodora* Pal'au (lemon verbena): a review of phytochemistry & pharmacology. *Journal of Ethnopharmacology*, *222*, 34–51.

Baldwin, E. A. (1993). Citrus fruit. In *Biochemistry of fruit ripening*. Springer.

Bampidis, V. A., & Robinson, P. H. (2006). Citrus by-products as ruminant feeds: A review. *Animal Feed Science & Technology*, *128*, 175–217. https://doi.org/10.1016/j.anifeedsci.2005.12.002

Beltrán, J. M. G., Espinosa, C., Guardiola, F. A., & Esteban, M. Á. (2017). Dietary dehydrated lemon peel improves the immune but not the antioxidant status of gilthead seabream (*Sparus aurata* L.). *Fish & Shellfish İmmunology*, *64*, 426–436.

Benamrouchea, S. L., & Madania, K. (2013). Phenolic contents and antioxidant activity of orange varieties (*Citrus sinensis* L. and *Citrus aurantium* L.) cultivated in Algeria: peels and leaves. *Industrial Crops Production*, *50*, 723–730.

Beygi, J. A., Moradlou, A. M. H., & Paknejzhad, H. (2019). Effect of dietary orange peel (*Citrus sinensis*) powder addition on growth performance in common carp (*Cyprinus carpio*). *Journal of Utilization & Cultivation of Aquatics*, *7*(4), 21–28. https://doi.org/10.22069/JAPU.2019.13727.1396

Bi, J., Li, H., & Wang, H. (2019). Delayed bitterness of citrus wine is removed through the selection of fining agents and fining optimization. *Frontiers in Chemistry*, *7*, 185. https://doi.org/10.3389/fchem.2019.00185

Boluda-Aguilar, M., García-Vidal, L., González-Castañeda, F. P., & López-Gómez, A. (2010). Mandarin peel wastes pretreatment with steam explosion for bioethanol production. *Bioresource Technology*, *101*, 3506–3513.

Boluda-Aguilar, M., & López-Gómez, A. (2013). Production of bioethanol by fermentation of lemon (*Citrus limon* L.) peel wastes pretreated with steam explosion. *Industrial Crop Production*, *41*, 188–197.

Breksa, A. P. I. I. I., Hidalgo, M. B., & Yuen, M. L. (2009). Liquid chromatography–electrospray ionisation mass spectrometry method for the rapid identification of citrus limonoid glucosides in citrus juices and extracts. *Food Chemistry*, *117*(4), 739–744. https://doi.org/10.1016/j.foodchem.2009.04.050

Burlow, S. M. (1994). Toxicological aspects of antioxidants used as food additives. In B. J. F. Hudson (Ed.), *Food antioxidants* (pp. 253–268). Elsevier.

Callaway, T. R., Carroll, J. A., Arthington, J. D., Edrington, T. S., Rossman, M. L., Carr, M. A., Krueger, N. A., Ricke, S. C., Crandall, P., & Nisbet, D. J. (2011a). *Escherichia coli* O157:H7 populations in ruminants can be reduced by orange peel product feeding. *Journal of Food Protection*, *74*, 1917–1921. https://doi.org/10.4315/0362-028X.JFP-11-234

Callaway, T. R., Carroll, J. A., Arthington, J. D., Edrington, T. S., Anderson, R. C., Rossman, M. L., Carr, M. A., Genovese, K. J., Ricke, S. C., Crandall, P., & Nisbet, D. J. (2011b). Orange peel products can reduce *Salmonella* populations in ruminants. *Foodborne Pathogens and Disease*, *8*, 1071–1075. https://doi.org/10.1089/fpd.2011.0867

Chavan, P., Singh, A. K., & Kaur, G. (2018). Recent progress in the utilization of industrial waste and by-products of citrus fruits: A review. *Journal of Food Process Engineering*, *41*, 12895.

Chekani, R., Akrami, R., Ghiasvand, Z., Chitsaz, H., & Jorjani, S. (2021). Effect of dietary dehydrated lemon peel (*Citrus limon*) supplementation on growth, hemato-immunolological and antioxidant status of rainbow trout (*Oncorhynchus mykiss*) under exposure to crowding stress. *Aquaculture*, *539*, 736597.

Costa, R., Dugo, P., Navarra, M., Raymo, V., Dugo, G., & Mondello, L. (2010). Study on the chemical composition variability of some pro- cessed bergamot (*Citrus bergamia*) essential oils. *Flavour and Fragrance Journal*, *25*(1), 4–12. https://doi.org/10.1002/ffj.1949

Dawood, M. A. O., El Basuini, M. F., Zaineldin, A. I., Yilmaz, S., Hasan, M. T., Ahmadifar, E., El Asely, A. M., Abdel-Latif, H. M. R., Alagawany, M., Abu-Elala, N. M., Van Doan, H., & Sewilam, H. (2021). Antiparasitic and antibacterial functionality of essential oils: an alternative approach for sustainable aquaculture. *Pathogens*, *10*, 185.

de Moraes Crizel, T., Jablonski, A., de Oliveira Rios, A., Rech, R., & Flôres, S. H. (2013). Dietary fiber from orange byproducts as a potential fat replacer. *LWT Food Science & Technology*, *53*, 9–14. https://doi.org/10.1016/j.lwt.2013.02.002

Debbarma, J., Kishore, P., Nayak, B. B., Kannuchamy, N., & Gudipati, V. (2013). Antibacterial activity of ginger, eucalyptus and sweet orange peel essential oils on fish-borne bacteria. *Journal of Food Processing & Preservation*, *37*(5), 1022–1030.

Demirci, B., Terzi, F., Kesbic, O. S., Acar, U., Yilmaz, S., & Kesbic, F. I. (2021). Does dietary incorporation level of pea protein isolate influence the digestive system morphology in rainbow trout (*Oncorhynchus mykiss*)? *Anatomia, Histologia, Embryologia*, *50*(6), 956–964. https://doi.org/10.1111/ahe.12740

Devatkal, S. K., Narsaiah, K., & Borah, A. (2010). Anti-oxidant effect of extracts of kinnow rind, pomegranate rind and seed powders in cooked goat meat patties. *Meat Science*, *85*(1), 155–159.

FAO. (2019). FAOSTAT [WWW Document] Food and Agricultural Organisation. United Nations. http://www.fao.org/faostat/en/#data/QC. (Accessed 13 April 2019).

FAO STAT. (2017). *Citrus fruit fresh and processed Statistical Bulletin 2016*. FAO STAT.

Fernández-Ginés, J. M., Fernández-López, J., Sayas-Barberá, E., Sendra, E., & Pérez-Alvarez, J. A. (2003). Effect of storage conditions on quality characteristics of Bologna sausages made with citrus fiber. *Journal of Food Science*, *68*, 710–715. https://doi.org/10.1111/j.1365-2621.2003.tb05737.x

Fishman, M. L., Chau, H. K., Hoagland, P., & Ayyad, K. (1999). Characterization of pectin, flash-extracted from orange albedo by microwave heating, under pressure. *Carbohydrate Research*, *323*, 126–138. https://doi.org/10.1016/S0008-6215(99)00244-X

Furné, M., Hidalgo, M. C., L'opez, A., García-Gallego, M., Morales, A. E., Domezain, A., Domezain'e, J., & Sanz, A. (2005). Digestive enzyme activities in Adriatic sturgeon *Acipenser naccarii* and rainbow trout *Oncorhynchus mykiss*. A comparative study. *Aquaculture*, *250*, 391–398.

Gallaugher, P., & Farrell, A. P. (1998). Hematocrit and blood oxygen-carrying capacity. In S. F. Perry & B. L. Tufts (Eds.), *Fish respiration* (p. 356). Academic Press.

Genovese, S., Fiorito, S., Locatelli, M., Carlucci, G., & Epifano, F. (2014). Analysis of biologically active oxyprenylated ferulic acid derivatives in Citrus fruits. *Plant Foods for Human Nutrition*, *69*(3), 255–260.

Gheytasi, A., Shekarabi, S. P. H., Islami, H. R., & Mehrgan, M. S. (2021). Feeding rainbow trout, *Oncorhynchus mykiss*, with lemon essential oil loaded in chitosan nanoparticles: effect on growth performance, serum hemato-immunological parameters, and body composition. *Aquaculture International*, *29*, 2207–2221.

Gmitter, F. G., & Hu, X. (1990). The possible role of Yunnan, China, in the origin of contemporary Citrus species (Rutaceae). *Economic Botany*, *44*, 267–277.

Gorinstein, S., Martin-Belloso, O., Park, Y. S., Haruenkit, R., Lojek, A., Ĉiž, M., Caspi, A., Libman, I., & Trakhtenberg, S. (2001). Comparison of some biochemical characteristics of different citrus fruits. *Food Chemistry*, *74*, 309–315. https://doi.org/10.1016/S0308-8146(01)00157-1

Goulas, V., & Manganaris, G. A. (2012). Exploring the phytochemical content and the antioxidant potential of citrus fruits grown in Cyprus. *Food Chemistry*, *131*(1), 39–47.

Guimarães, R., Barros, L., Barreira, J. C. M., Sousa, M. J., & Carvalho, A. M. (2009). Ferreira ICFR. Targeting excessive free radicals with peels and juices of citrus fruits: grapefruit, lemon, lime, and orange. *Food & Chemical Toxicology*, *48*(1), 99–106.

Güleç, A. K., Danabaş, D., Ural, M., Şeker, E., Arslan, A., & Serdar, O. (2013). Effect of mixed use of thyme and fennel oils on biochemical properties and electrolytes in rainbow trout as a response to *Yersenia ruckeri* infection. *Acta Veterinaria Brno*, *82*, 297–302.

Gültepe, N. (2018). How the use of orange (*Citrus sinensis*) peel essential oil affected the growth performance of rainbow trout (*Oncorhynchus mykiss*)?. Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. *Animal Science & Biotechnologies*, *75*(1), 16–20.

Gültepe, N. (2020). Protective effect of D-limonene derived from orange peel essential oil against *Yersinia ruckeri* in rainbow trout. *Aquaculture Reports*, *18*, 100417.

Harikrishnan, R., Thamizharasan, S., Devi, G., van Doan, H., Ajith Kumar, T. T., Hoseinifar, S. H., & Balasundaram, C. (2020). Dried lemon peel enriched diet improves antioxidant activity, immune response and modulates immuno-antioxidant genes in *Labeo rohita* against *Aeromonas sorbia*. *Fish & Shellfish Immunology*, *106*, 675–684.

Hasegawa, S., & Miyake, M. (1996). Biochemistry and biological functions of citrus limonoids. *Food Reviews International*, *12*(4), 413–435. https://doi.org/10.1080/87559129609541089

Hassaan, M. S., Mohammady, E. Y., Adnan, A. M., Abd Elnabi, H. E., Ayman, M. F., Soltan, M. S., & El-Haroun, E. R. (2020). Effect of dietary protease at different levels of malic acid on growth, digestive enzymes and haemato-immunological responses of Nile tilapia,

fed fish meal free diets. *Aquaculture*, *522*, 735124. https://doi.org/10.1016/j.aquaculture.2020.735124
Hassaan, M. S., Mohammady, E. Y., Soaudy, M. R., El-Garhy, H. A. S., Moustafa, M. M. A. M., Mohamed, S. A., & El-Haroun, E. R. (2019). Effect of *Silybum marianum* seeds as a feed additive on growth performance, serum biochemical indices, antioxidant status, and gene expression of Nile tilapia, *Oreochromis niloticus* (L.) fingerlings. *Aquaculture*, *509*, 178–187.
Hassaan, M. S., Mohammady, E. Y., Soaudy, M. R., Sabae, S. A., Mahmoud, A. M. A., & El-Haroun, E. R. (2021). Comparative study on the effect of dietary β-carotene and phycocyanin extracted from *Spirulina platensis* on immune-oxidative stress biomarkers, genes expression and intestinal enzymes, serum biochemical in Nile tilapia, *Oreochromis niloticus*. *Fish & Shellfish Immunology*, *108*, 63–72.
Hool, L. C. (2006). Reactive oxygen species in cardiac signaling: from mitochondria to plasma membrane ion channels. *Clinical & Experimental Pharmacology & Physiology*, *33*, 146–151.
Hoseinifar, S. H., Ahmadi, A., Khalili, M., Raeisi, M., Van Doan, H., & Caipang, C. M. (2017). The study of antioxidant enzymes and immune-related genes expression in common carp (*Cyprinus carpio*) fingerlings fed different prebiotics. *Aquaculture Research*, *48*(11), 5447–5454.
Huang, R. P., Golard, A., Hossain, M. Z., Huang, R., Liu, Y. G., & Boynton, A. L. (2001). Hydrogen peroxide promotes transformation of rat liver non-neoplastic epithelial cells through activation of epidermal growth factor receptor. *Molecular Carninogenesis*, *30*, 209–217.
Kawahara, E., Ueda, T., & Nomura, S. (1991). In vitro phagocytic activity of white-spotted char blood cells after injection with *Aeromonas salmonicida* extracellular products. *Fish Pathology*, *26*(4), 213–214. https://doi.org/10.3147/jsfp.26.213
Kesbiç, O. S., Acar, Ü., Yilmaz, S., & Aydin, Ö. D. (2020). Effects of bergamot (*Citrus bergamia*) peel oil-supplemented diets on growth performance, haematology, and serum biochemical parameters of Nile tilapia (*Oreochromis niloticus*). *Fish Physiology and Biochemistry*, *46*(1), 103–110.
Kurowska, E. M., & Manthey, J. A. (2004). Hypolipidemic effects and absorption of citrus polymethoxylated flavones in hamsters with diet-induced hypercholesterolemia. *Journal of Agricultural & Food Chemistry*, *52*, 2879–2886. https://doi.org/10.1021/jf035354z
Ladaniya, M. S. (2008a). *Citrus Fruit: Biology, Technology & Evaluation* (pp. 1–10). Elsevier. https://doi.org/10.1016/B978-012374130-1.50003-6
Ladaniya, M. S. (2008b). Commercial fresh citrus cultivars and producing countries. In *Citrus Fruit: Biology, Technology & Evaluation* (pp. 13–65). Academic Press.
Laein, S. S., Salari, A., Shahsavani, D., & Baghshani, H. (2021). Effect of supplementation with lemon (*Citrus limon*) pomace powder on the growth performance and antioxidant responses in common carp (*Cyprinus carpio*). *Journal of Biological and Environmental Sciences*, *15*(44), 47–54.
Lopes, J. M., de Freitas Souza, C., Saccol, E. M. H., Pavanato, M. A., Antoniazzi, A., Rovani, M. T., Heinzmann, B. M., & Baldisserotto, B. (2019). *Citrus aurantium* essential oil as feed additive improved growth performance, survival, metabolic, and oxidative parameters of silver catfish (*Rhamdia quelen*). *Aquaculture Nutrition*, *25*(2), 310–318.
Lopes, J. M., Marques, N. C., dos Santos, M. D. M. C., Souza, C. F., Baldissera, M. D., Carvalho, R. C., Santos, L. L., Pantoja, B. T. S., Heinzmann, B. M., & Baldisserotto, B. (2020). Dietary limon *Citrus × latifolia* fruit peel essential oil improves antioxidant capacity of tambaqui (*Colossoma macropomum*) juveniles. *Aquaculture Research*, *51*, 4852–4862.
López-Romero, D., Izquierdo-Vega, J. A., Morales-González, J. A., Madrigal-Bujaidar, E., Chamorro-Cevallos, G., Sánchez-Gutiérrez, M., Betanzos-Cabrera, G., Alvarez-Gonzalez, I., Morales-González, Á., & Madrigal-Santillán, E. (2018). Evidence of some natural products with antigenotoxic effects. Part 2: Plants, vegetables, and natural resin. *Nutrients*, *10*(12), 1954. https://doi.org/10.3390/nu10121954
MacLennan, A. H., Wilson, D. H., & Taylor, A. W. (2002). The escalating cost and prevalence of alternative medicine. *Preventive Medicine*, *35*, 166–173. https://doi.org/10.1006/pmed.2002.1057
Mahato, N., Sharma, K., Sinha, M., & Cho, M. H. (2018). Citrus waste derived nutra/pharmaceuticals for health benefits: Current trends and future perspectives. *Journal of Functional Foods*, *40*, 307–316. https://doi.org/10.1016/j.jff.2017.11.015
Mamma, D., Kourtoglou, E., & Christakopoulos, P. (2008). Fungal multienzyme production on industrial byproducts of the citrus-processing industry. *Bioresource Technology*, *99*, 2373–2383.
Mancuso, M., Catalfamo, M., Laganà, P., Rappazzo, A. C., Raymo, V., Zampino, D., & Zaccone, R. (2019). Screening of antimicrobial activity of citrus essential oils against pathogenic bacteria and Candida strains. *Flavour and Fragrance Journal*, *34*(3), 187–200. https://doi.org/10.1002/ffj.3491
Manners, G. D. (2007). Citrus limonoids: analysis, bioactivity, and biomedical prospects. *Journal of the Science of Food & Agriculture*, *55*(21), 8285–8294.
Manthey, J. A., & Grohmann, K. (2001). Phenols in citrus peel byproducts. Concentrations of hydroxycinnamates and polymethoxylated flavones in citrus peel molasses. *Journal of Agricultural and Food Chemistry*, *49*(7), 3268–3273.
Marín, F. R., Martinez, M., Uribesalgo, T., Castillo, S., & Frutos, M. J. (2002). Changes in nutraceutical composition of lemon juices according to different industrial extraction systems. *Food Chemistry*, *78*, 319–324. https://doi.org/10.1016/S0308-8146(02)00102-4
Marín, F. R., Soler-Rivas, C., Benavente-García, O., Castillo, J., & Pérez-Alvarez, J. A. (2007). By-products from different citrus processes as a source of customized functional fibers. *Food Chemistry*, *100*(2), 736–741.
Mehta, N., Ahlawat, S. S., Sharma, D. P., & Dabur, R. S. (2015). Novel trends in development of dietary fiber rich meat products—A critical review. *Journal of Food Science & Technology*, *52*, 633–647. https://doi.org/10.1007/s13197-013-1010-2
Menichini, F., Tundis, R., Loizzo, M. R., Bonesi, M., D'Angelo, D., Lombardi, P., & Mastellone, V. (2015). *Citrus medica* L. cv Diamante (Rutaceae) peel extract improves glycaemic status of Zucker diabetic fatty (ZDF) rats and protects against 631 oxidative stress. *Journal of Enzyme Inhibition and Medicinal Chemistry*, *8*, 1–7. https://doi.org/10.3109/14756366.2015.1115400633
M'hiri, N., Ioannou, I., Ghoul, M., & Boudhrioua, N. M. (2016). Comparison of the efficiency of different extraction methods on antioxidants of maltease orange peel. *International Journal of Food Sciences & Nutrition*, *3*, 1–13.
M'hiri, N., Ioannou, I., Ghoul, M., & Boudhrioua, N. M. (2017). Phytochemical characteristics of citrus peel and effect of conventional and nonconventional processing on phenolic compounds: A review conventional and nonconventional processing on phenolic. *Food Reviews International*, *33*, 587–619. https://doi.org/10.1080/87559129.2016.1196489
Milos, M., Mastelic, J., & Jerkovic, I. (2000). Chemical composition and antioxidant effect of glycosidically bound volatile compounds from oregano, *Origanum vulgare* L. ssp. *Food Chemistry*, *71*, 79–83.
Min, B., Bae, I. Y., Lee, H. G., Yoo, S. H., & Lee, S. (2010). Utilization of pectin-enriched materials from apple pomace as a fat replacer in a model food system. *Bioresource Technology*, *101*, 5414–5418.
Miyake, Y., Suzuki, E., Ohya, S., Fukumoto, S., Hiramitsu, M., Sakaida, K., Osawa, T., & Furuichi, Y. (2006). Lipid lowering effect of eriocitrin, the main flavonoid in lemon fruit, in rats on a high-fat and high-cholesterol diet. *Journal of Food Science*, *71*, 633–637. https://doi.org/10.1111/j.1750-3841.2006.00192.x
Mohamed, R. A., Yousef, Y. M., El-Tras, W. F., & Khalafallaa, M. M. (2021). Dietary essential oil extract from sweet orange (*Citrus

sinensis) and bitter lemon (*Citrus limon*) peels improved Nile tilapia performance and health status. *Aquaculture Research*, *52*, 1463–1479.

Mohammady, E. Y., Soaudy, M. R., Abdel-Rahman, A., Abdel-Tawwab, M., & Hassaan, M. S. (2021). Comparative effects of dietary zinc forms on performance, immunity, and oxidative stress-related gene expression in Nile tilapia, *Oreochromis niloticus*. *Aquaculture*, *532*, 736006. https://doi.org/10.1016/j.aquaculture.2020.736006

Moure, A., Cruz, J. M., Franco, D., Dominguez, J. M., Sineiro, J., Nunez, M. J., & Parajo, J. C. (2001). Natural antioxidants from residual sources. *Food Chemistry*, *72*, 145–171.

Mulvihill, E. E., & Huff, M. W. (2012). Citrus flavonoids and the prevention of atherosclerosis. *Cardiovascular & Hematological Disorders Drug Targets*, *12*(2), 84–91.

Nam, I. S., Garnsworthy, P. C., & Ahn, J. H. (2006). Supplementation of essential oil extracted from citrus peel to animal feeds decreases microbial activity and aflatoxin contamination without disrupting in vitro ruminal fermentation. *Asian- Australasian Journal of Animal Sciences*, *19*, 1617–1622.

Namitha, K. K., & Negi, P. S. (2010). Chemistry and biotechology of carotenoids. *Chemistry, Medicine, Critical Reviews in Food Science & Nutrition*, *50*, 728–760. https://doi.org/10.1080/10408398.2010.499811

Negro, V., Mancini, G., Ruggeri, B., & Fino, D. (2016). Citrus waste as feedstock for biobased products recovery: Review on limonene case study and energy valorization. *Bioresource Technology*, *214*, 806–815. https://doi.org/10.1016/j.biortech.2016.05.006

Ngugi, C. C., Oyoo-Okoth, E., & Muchiri, M. (2017). Effects of dietary levels of essential oil (EO) extract from bitter lemon (*Citrus limon*) fruit peels on growth, biochemical, haemato-immunological parameters and disease resistance in Juvenile *Labeo victorianus* fingerlings challenged with *Aeromonas hydrophila*. *Aquaculture Research*, *48*(5), 2253–2265.

Oberoi, H. S., Vadlani, P. V., Nanjundaswamy, A., Bansal, S., Singh, S., Kaur, S., & Babbar, N. (2011). Enhanced ethanol production from *Kinnow mandarin* (*Citrus reticulata*) waste via a statistically optimized simultaneous saccharification and fermentation process. *Bioresource Technology*, *102*(2), 1593–1601.

Oikeh, E., Oriakhi, K., & Omoregie, E. (2013). Proximate analysis and phytochemical screening of *citrus sinensis* fruit wastes. *Bioscience*, *1*, 164–170.

Öntaş, C., Baba, E., Kaplaner, E., Küçükaydin, S., Öztürk, M., & Ercan, M. D. (2016). Antibacterial activity of *Citrus limon* peel essential oil and *Argania spinosa* oil against fish pathogenic bacteria. *Kafkas Universitesi Veteriner Fakultesi Dergisi*, *22*(5), 741–749.

Ozogul, Y., Kuley, E., Uçar, Y., & Ozogul, F. (2015). Antimicrobial impacts of essential oils on food borne-pathogens. *Recent Patents on Food, Nutrition & Agriculture*, *7*(1), 53–61.

Panwar, D., Panesar, P. S., & Chopra, H. (2019). Recent trends on the valorization strategies for the management of citrus by-products. *Food Reviews International*, *37*(1), 1–30.

Pathirana, H. N., Wimalasena, S. H., De Silva, B. C., Hossain, S., & Heo, G. J. (2018). Antibacterial activity of lime (*Citrus aurantifolia*) essential oil and limonene against fish pathogenic bacteria isolated from cultured olive flounder (*Paralichthys olivaceus*). *Fisheries & Aquatic Life*, *26*(2), 131–139. https://doi.org/10.2478/aopf-2018-0014

Pellegrini, N., Serafini, M., Colombi, B., Rio, D. D., Salvatore, S., & Bianchi, M. (2003). Total antioxidant capacity of plant foods, beverages and oils consumed in Italy assessed by three different in vitro assays. *Journal of Nutrition*, *133*, 2812–2819.

Perry, G., Raine, K. A., Nunomura, A., Watayc, T., Sayre, L. M., & Smith, M. A. (2000). How important is oxidative damage? Lessons from Alzheimer's disease. *Free Radical Biology and Medicine*, *28*, 831–834.

Peterson, J. J., Beecher, G. R., Bhagwat, S. A., Dwyer, J. T., Gebhardt, S. E., & Haytowitz, D. B. (2006). Flavanones in grapefruit, lemons, and limes: A compilation and review of the data from the analytical literature. *Journal of Food Composition and Analysis*, *19*, 74–S80.

Qin, S., Lv, C., Wang, Q., Zheng, Z., Sun, X., Tang, M., & Deng, F. (2018). Extraction, identification, and antioxidant property evaluation of limonin from pummelo seeds. *Animal Nutrition*, *4*(3), 281–287. https://doi.org/10.1016/j.aninu.2018.05.005

Rapisarda, P., Tomaino, A., Cascio, R. L., Bonina, F., Pasquale, A. D., & Saija, A. (1999). Antioxidant effectiveness as influenced by phenolic content of fresh orange juices. *Journal of Agricultural and Food Chemistry*, *47*(11), 4718–4723.

Russo, M., Arigò, A., Calabrò, M. L., Farnetti, S., Mondello, L., & Dugo, P. (2016). Bergamot (*Citrus bergamia risso*) as a source of nutraceuticals: Limonoids and flavonoids. *Journal of Functional Foods*, *20*, 10–19. https://doi.org/10.1002/jsfa.4383

Sadeghi, F., Ahmadifar, E., Shahriari Moghadam, M., Ghiyasi, M., Dawood, M. A. O., & Yilmaz, S. (2021). Lemon, *Citrus aurantiifolia*, peel and *Bacillus licheniformis* protected common carp, *Cyprinus carpio*, from *Aeromonas hydrophila* infection by improving the humoral and skin mucosal immunity, and antioxidative responses. *Journal of the World Aquaculture Society*, *52*, 124–137.

Safaeian Laein, S., Salari, A., Shahsavani, D., & Baghshani, H. (2018). Effect of lemon (*Citrus lemon*) pumace powder supplementation on growth performance, lipid peroxidation and protein oxidation biomarkers in some tissues of common carp (*Cyprinus carpio*). *Iranian Journal of Veterinary Science & Technology*, *10*(2), 55–63. https://doi.org/10.22067/veterinary.v2i10.73469

Salem, M., & Abdel-Ghany, H. M. (2018). Effects of dietary orange peel on growth performance of Nile tilapia (*Oreochromis niloticus*) fingerlings. *Aquaculture Studies*, *18*, 127–134.

Samavat, Z., Shamsaie, M., Jamili, S., Soltani, M., & Hosseini, S. P. (2019). Determination of grapefruit (*Citrus paradisi*) peel extract bio-active substances and its application in Caspian white fish (*Rutilus frisii kutum*) diet: Growth, haemato-biochemical parameters and intestinal morphology. *Aquaculture Research*, *50*(9), 2496–2504.

Satari, B., & Karimi, K. (2018). Citrus processing wastes: Environmental impacts, recent advances, and future perspectives in total valorization. *Resources, Conservation & Recycling*, *129*, 153–167.

Satari, B., Palhed, J., Karimi, K., Lundin, M., Taherzadeh, M. J., & Zamani, A. (2017). Process optimization for citrus waste biorefinery via simultaneous pectin extraction and pretreatment. *BioResources*, *12*, 1706–1722. https://doi.org/10.15376/biores.12.1.1706-1722

Saurabh, S., & Sahoo, P. (2008). Lysozyme: An important defence molecule of fish innate immune system. *Aquaculture Research*, *39*(3), 223–239.

Sáyago-Ayerdi, S. G., Brenes, A., & Goñi, I. (2009). Effect of grape antioxidant dietary fiber on the lipid oxidation of raw and cooked chicken hamburgers. *LWT Food Science & Technology*, *42*, 971–976. https://doi.org/10.1016/j.lwt.2008.12.006

Schieber, A., Stintzing, F. C., & Carle, R. (2001). By-products of plant food processing as a source of functional compounds recent developments. *Food Science & Technology*, *12*, 401–413.

Shabana, M. S., Karthika, M., & Ramasubramanian, V. (2019). Effect of dietary *Citrus sinensis* peel extract on growth performance, digestive enzyme activity, muscle biochemical composition, and metabolic enzyme status of the freshwater fish, *Catla catla*. *The Journal of Basic and Applied Zoology*, *80*(1), 51.

Sivropoulou, A., Papanikolaou, E., Nikolaou, C., Kokkini, S., Lanaras, T., & Arsenakis, M. (1996). Antimicrobial and cytotoxic activities of *Origanum* essential oils. *Journal of Agricultural & Food Chemistry*, *44*(5), 1202–1205.

Toutou, M. M., Soliman, A. A., Elokaby, M. A., Ahmed, R. A., & Baghdady, E. S. (2018). Growth performance and biochemical blood parameters of Nile tilapia, *Oreochromis niloticus*, and thinlip mullet, *Liza ramada*, fed a diet supplemented with lemon (*Citrus aurantifolia*) peel in a polyculture system. *Egyptian Journal of Aquatic Biology & Fisheries*, *22*(3), 183–192.

USDA. (2019). *United States Department of Agriculture/Foreign Agricultural Service, 2019. Citrus: World Markets and Trad*. World Markets and Trade. http://www.fas.usda.gov

Vicente, I. S., Fleuri, L. F., Carvalho, P. L. P. F., Guimarães, M. G., Naliato, R. F., de Carvalho Müller, H., Sartori, M. M. P., Pezzato, L. E., & Barros, M. M. (2019). Orange peel fragment improves antioxidant capacity and haematological profile of Nile tilapia subjected to heat/dissolved oxygen-induced stress. *Aquaculture Research*, *50*(1), 80–92.

Wang, L., Wang, J., Fang, L., Zheng, Z., Zhi, D., Wang, S., Li, S., Ho, C. T., & Zhao, H. (2014). Anticancer activities of citrus peel polymethoxy flavones related to angiogenesis and others. *BioMed Research International*, *2014*, 453972. https://doi.org/10.1155/2014/453972

Wang, Y. C., Chuang, Y. C., & Hsu, H. W. (2008). The flavonoid, carotenoid and pectin content in peels of citrus cultivated in Taiwan. *Food Chemistry*, *106*(1), 277–284.

Watanuki, H., Ota, K., Tassakka, A. C. M. A. R., Kato, T., & Sakai, M. (2006). Immunostimulant effects of dietary *Spirulina platensis* on carp, *Cyprinus carpio*. *Aquaculture*, *258*(1), 157–163.

Webber, H. J. (1967). *History and development of the citrus industry*. Division of Agricultural Sciences, University of California.

World Data Atlas. (2021). World - Citrus fruit production quantity. https://knoema.com/atlas/World/topics/Agriculture/Crops-Production-Quantity-tonnes/Citrus-fruit-production

Wu, T., Luo, J., & Xu, B. (2015). In vitro antidiabetic effects of selected fruits and vegetables against glycosidase and aldose reductase. *Food Science & Nutrition*, *3*, 495–505. https://doi.org/10.1002/fsn3.243

Yilmaz, S. (2019a). Effects of dietary blackberry syrup supplement on growth performance, antioxidant, and immunological responses, and resistance of Nile tilapia, *Oreochromis niloticus* to *Plesiomonas shigelloides*. *Fish & Shellfish Immunology*, *84*, 1125–1133.

Yilmaz, S. (2019b). Effects of dietary caffeic acid supplement on antioxidant, immunological and liver gene expression responses, and resistance of Nile tilapia, *Oreochromis niloticus* to *Aeromonas veronii*. *Fish & Shellfish Immunology*, *86*, 384–392.

Zema, D. A., Fòlino, A., Zappia, G., Calabrò, P. S., Tamburino, V., & Marcello, S. (2018). Anaerobic digestion of orange peel in a semi-continuous pilot plant: An environmentally sound way of citrus waste management in agro-ecosystems. *Science of the Total Environment*, *630*, 401–408. https://doi.org/10.1016/j.scitotenv.2018.02.168

Zhu, F. (2020). A review on the application of herbal medicines in the disease control of aquatic animals. *Aquaculture*, *526*, 735422.

Zou, Z., Xi, W., Hu, Y., Nie, C., & Zhou, Z. (2016). Antioxidant activity of Citrus fruits. *Food Chemistry*, *196*, 885–896.

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