



## Applications of citrus peels valorisation in circular bioeconomy

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### ABSTRACT

Plant-derived biomass, in particular, offers a raw material that is potentially cost effective in producing affordable food, energy, feed, sanitation, and clean drinking water. Citrus fruits have been extensively documented for their beneficial health effects and significant contribution to agricultural waste worldwide as fruit peels, which are often discarded and hence remain unexploited. Polyphenols found in citrus peels have health-promoting benefits and serve as catalysts/resources for producing valuable ingredients. The current review highlights the exploitation of citrus peels in the production of biofuels, essential oils, bio-based nanomaterials, and the enrichment of functional foods, thus highlighting their nutritional and health benefits. Conclusively, the review comprehensively aligns with sustainable practices in the agro-industrial sector, alongside the circular bioeconomy concept.

### 1. Introduction

In recent years, the utilization and management of waste materials through treatment, reuse, and recycling have become increasingly important in the food industry and agriculture [1]. The focus on organic material recycling has been rapidly growing in conjunction with greater progress in the bioeconomy as well as the overarching circular economy concept [1]. These elements are often combined with the concept of circular bioeconomy [2]. Attempts have been made to meet the European Green Deal (EGD) and climate targets, which require a transition from fossil fuel-dependent economies to a more sustainable and circular bioeconomy [3]. The concept of circular bioeconomy (CBE) greatly diverges from the traditional approaches for waste recycling. The CBE

model emphasizes the recovery and safeguarding of the robustness of productive ecosystems [4]. Carus and Dammer [5] documented that “the concept of a circular bioeconomy involves utilizing renewable bio-resources and converting them, along with their by-products, into valuable commodities including food, bioenergy, and animal feed.” This strategy generates new employment opportunities.

Citrus fruits are classified under the family *Rutaceae*, are widely distributed across the globe, and serve as a rich source of valuable secondary metabolites [6]. Citrus fruit production has surpassed 124 million tons annually, of which roughly one-third of the produced fruit undergoes processing. Consequently, a considerable amount of residue is generated every year [7,8]. Citrus peel comprises a significant proportion of the overall fruit weight and forms the primary residue [9]. A

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study by Castro-Vazquez et al. [10] discovered that citrus peels act as principal reservoirs of polyphenols in these fruits. Peels of bitter and sweet oranges, mandarins, and lemons have been documented to contain significant quantities of phenolic acids and flavonoids, particularly flavanones, glycosylated flavanones, and polymethoxyflavones (PMFs) [10]. These bioactive compounds possess various therapeutic qualities, including antiallergenic, anti-inflammatory, antiatherogenic, antimicrobial, antithrombotic, cardioprotective, vasodilatory, and anticarcinogenic effects (Table 1) [10]. Citrus peel waste accounts for nearly 50–70% of the total processed fruit weight. The exact percentages might vary based on the specific fruit cultivar and the technology used [24]. Zema et al. [25] found that the worldwide annual output of orange peel as trash is approximately ten million metric tons. The waste generated from oranges is comparable to that of other citrus fruits, and comprise approximately 30–35% seeds and pulp, and 60–65% peels [26]. In 2016, the global production of citrus waste amounting to approximately 25 million tons was reported, with orange peels contributing the majority of it [27]. The 2018 global pomelo peel output was anticipated to be approximately between 2.8 and 4.7 million tons [28]. Citrus peels are normally dumped without being subjected to additional processing or practical reuse, thus resulting in significant damage to the environment [9]. Poor fruit waste management may pose a substantial environmental risk due to their potential for biodegradation and fermentation. Numerous researchers across the globe have examined the beneficial bioactive chemical compounds found in various citrus peel species, along with the efficient extraction procedures employed for the extraction of these compounds from their fruit peel [29]. Consequently, limited attention has been paid to the use of peels for the development of biologically derived micro-or nanomaterials and meals with specific functions.

The worldwide recycling of food waste and its value-addition have been a significant growing field for sustainable research in recent years. The United Nations (UN) promotes food waste management as a means of accomplishing numerous Sustainable Development Goals (SDGs), such as SDG 2, which aims to eradicate hunger; SDG 3, which ensures good health and promotes well-being; SDG 6, which ensures the availability of clean water and sanitation; SDG 7, which provides affordable, reliable, sustainable, and modern energy; and SDG 12, which promotes sustainable consumption and production [30]. Hence, the primary objective of the current review is to comprehend the development of carbon dots and green metallic nanoparticles generated from the peels of citrus fruits, subsequently highlighting their wide array of applications in therapeutics and industry. The second objective was to provide information relating to the use of bio-adsorbents and biochar prepared from citrus peels, along with their importance in the environmental and agricultural sectors. The third objective was to investigate the potential of utilizing biodiesel derived from citrus fruit peels as a sustainable and practical energy alternative. The fourth objective was to examine the prospective utilization of citrus peel-based essential oil. The fifth objective is to ensure the efficient use of citrus peels to improve overall food quality, such as cereal-based foods, edible films/coatings, and various other food items.

## 2. Citrus peels polyphenols

Polyphenols constitute a large category of secondary metabolites isolated from plants, biosynthetically obtained from the shikimic acid pathway and structurally characterized by presence of aromatic rings containing one or more hydroxy groups [31]. Flavonoids, stilbenes, lignans, and tannins are the main polyphenolic groups; additionally, other phenolic compounds, such as phenolic acids (e.g., caffeic acid, cinnamic acid, and gallic acid), also produced through the same pathway as other compounds, comprise this class [31]. Polyphenolic compounds obtained from citrus peels play an important role in the eco-friendly production of nanoparticles in an eco-friendly manner. The functional groups present in these polyphenols significantly affect the

efficacy of biochar, bio-adsorbent materials, and green carbon dots. In addition, the quantity of polyphenolics affects the taste of functional feeds and foods. The subsequent paragraphs offer a concise explanation of the various categories of polyphenols found in diverse citrus peels.








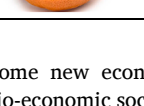
Shehata et al. [11] examined the compounds extracted from *Citrus sinensis* and sweet orange peels using highly efficient liquid chromatographic analysis in combination with mass spectrometry. This study identified more than 40 polyphenols, including flavonoids and phenolic acids. Notably, some of these compounds have not been documented previously. The major polyphenolic compounds identified include narirutin, hesperetin-7-O-rutinoside, sakuranetin, naringin, naringenin, hesperetin, quinic acid, and datscetin-3-O-rutinoside. Furthermore, the extract from sweet orange peel exhibited most significant outcomes with respect to the scavenging ABTS ((2,2'-azinobis (3-ethylbenzothiazoline-6-sulfonic acid)), DPPH (2,2-diphenyl-1-picrylhydrazyl), and hydroxyl radicals. High-performance liquid chromatographic (HPLC) analysis of orange peel showed that the methanolic extract exhibited highest quantities of nobiletin and hesperidin, measuring 8.50 and 133.70 mg/g, respectively. Comparing the concentrations of nobiletin and hesperidin in the ethanolic extract were 5.50 and 98.80 mg/g, whereas in the aqueous extract, the concentrations were 1.25 and 61.90 mg/g, respectively [12]. A combination of aqueous-methanol solvent systems was preferred for the extraction of flavonoids from orange peels. Extraction was performed for 60 min. Another study by Safdar et al. [13] detected a total of six flavonoids and five phenolic acids present in the *Citrus reticulata* L. or kinnow using HPLC. Hesperidin and ferulic acid were the principal phenolic compounds detected in kinnow peel extracts, whereas caffeic acid was the least prevalent. Liu et al. [9] employed food-grade solvents, such as ethanol or hot water, to extract polyphenolic compounds from lemon (*Citrus lemon*) and mandarin (*Citrus reticulata*) peels using HPLC. Their findings revealed the presence of 12 polyphenols, including 10 flavonoids and two phenolic acids. Among these, hesperidin and narirutin were the most widespread. Peiró and scholars [32] have shown that the application of a pulsed electric field (PEF) at 7 kV/cm intensity led to a 3-fold improvement in polyphenol extraction efficiency from lemon peel. The maximum fresh weight (FW) of 84 mg/100 g was measured for hesperidin and 176 mg/100 g of FW for eriocitrin. Therefore, PEF presents a novel approach for enhancing polyphenol extraction using an environmentally friendly, non-thermal technology, thereby increasing the economic benefits of industrial processes.

Flavonoids have been isolated from the peels of *Citrus paradise* and grapefruit by Garcia-Castello et al. [33] using both traditional solid-liquid extraction (CE) and ultrasonic-aided extraction (USE). The study findings revealed the presence of naringin in the extracts, with values ranging between 24 and 36 mg/g the dw for USE and 18–28 mg/g for DW for CE. Luteolin and procyanidin B dimers were found in sweet lime or *Citrus limetta* peels for the first time by Buyukkurt et al. [18]. The researchers utilized Electrospray ionization tandem mass spectrometry (LC-DAD-ESI-MS/MS) was combined with liquid chromatography (LC). The primary chemical isolated was hesperidin (hesperidin). Furthermore, HPLC analysis of the methanolic extracts from *Citrus aurantium* L. and bitter orange peels showed that phenolic acids constituted the major proportion of the phenolics, accounting for approximately 73.80% of the overall content. Conversely, the flavonoid content was 23.02% of the total flavonoid content. The primary phenolic compounds constituted p-coumaric acids and ferulic acids up to 23.79% and 24.68% of the fruit peel, respectively [34].

## 3. Citrus peels valorisation and its socio-economic impact

Bioeconomy based on citrus wastes is a sundry field dealing with different types of industrial and agricultural activities [35]. Citrus wastes and their by-products have recently been attaining significance and considered for developing a potential bioeconomy approach by conversion of waste into valorised products [35]. These wastes have

**Table 1**  
The biological activity of polyphenols derived from certain citrus peels.

Type of citrus fruit	Polyphenols	Biological activities	Reference
 <i>Citrus sinensis</i>	<b>Flavonoids:</b> Naringenin, narirutin, hesperetin, vitexin, kaempferol-3-O-arabinoside, cyanidin-3-O-alpha-arabinoside, cirsimaritin, catechol; <b>Phenolic acids:</b> Feruloylquinic acid	Antioxidant; antimicrobial	[11,12]
 <i>Citrus reticulata</i> L.	<b>Flavonoids:</b> Hesperidin, naringenin, kaempferol, quercetin, catechins, epicatechins; <b>Phenolic acids:</b> Gallic acid, chlorogenic acid, ferulic acid, coumaric acid, caffeic acid	Antioxidant; antifungal	[9,13]
 <i>Citrus grandis</i> L.	<b>Flavonoids:</b> Naringin, naringenin, narirutin, hesperidin, tangeretin, neodiosmin, nobiletin; <b>Phenolic acids:</b> Gallic acid, chlorogenic acid, ferulic acid, caffeic acid, sinapic acid, coumaric acid	Antioxidant; anti-inflammatory; antimicrobial; anti-nervous disorder; anti-metabolic disorder activities	[14,15]
 <i>Citrus paradisi</i> Macf.	<b>Flavonoids:</b> Naringin, isonaringin, hesperidin, naringenin, hesperetin, nobiletin, tangeretin; <b>Phenolic acids:</b> Gallic acid, protocatechuic acid, chlorogenic acid, <i>p</i> -hydroxybenzoic acid, ferulic acid, caffeic acid, sinapinic acid, coumaric acid, syringic acid	Antioxidant; cytoprotective effect	[10,16]
 <i>Citrus limetta</i>	<b>Flavonoids:</b> Luteolin, hesperidin, eriocitrin, procyanidin B dimer; <b>Phenolic acids:</b> Ferulic acid, caffeic acid	Antioxidant; anti-inflammatory; antimalarial activity	[17,18]
 <i>Citrus limon</i>	<b>Flavonoids:</b> Eriocitrin, hesperidin, hesperetin, vicenin-2, kaempferol-3-O-rutinoside; <b>Phenolic acids:</b> Caffeic acid, chlorogenic acid, gallic acid, <i>p</i> -coumaric acid	Antioxidant; antimicrobial; anti-inflammatory; antidiabetic, anti-obesogenic, anti-urolithic	[19,20]
 <i>Citrus macroptera</i>	<b>Flavonoids:</b> (-)-epicatechin, kaempferol; <b>Phenolic acids:</b> Caffeic acid, benzoic acid, syringic acid	Antioxidant; cardio-protective activity	[21,22]
 <i>Citrus aurantium</i>	<b>Flavonoids:</b> Neoeriocitrin, naringin, neohesperidin, neodiosmin, melitidin, nobiletin, tangeretin	Antiedematogenic activity	[23]

become new economically important supply chain sources and for socio-economic society benefits [36]. It is also important to analyze the current management practices for identification of the problems as well as future prospects [37]. Fernández-López and co-workers [38] have reported that the dietary fiber generated from citrus waste contains a higher cellulose proportion, which attributes for high soluble dietary fibers amount than wheat bran [39]. Also, the waste is rich in antioxidants like C-vitamin and flavonoids [38]. The fibers intake from citrus by-products aids in prevention of fiber deficiency amongst humans, furthermore, owing to its functional properties, the citrus fiber serves as a good fat substitute in ice cream, reducing the ice cream fat by about 70% [40].

Citrus waste holds a phenomenal potential in production of biofuel and biogas [41]. The biogas yield from one-ton of citrus by-products is around 89.3 Nm<sup>3</sup>, depending upon various factor [42,43]. The major orange growing nations are heading towards utilization of citrus

by-products as a source of bioenergy or for biogas production [35]. The poly limonene carbonate (PLC) produced from citrus waste helps in improvement of the plastic industry's overall sustainability by contribution to the circular economy [44]. Durkin et al. [44] have suggested from the modelling results that a process for producing 21 kilotonne/-year PLC is technically possible through an economic potential amounting to about 21.4 M USD/year. The upcoming sections as well as sub-sections provide details about the various value-added products prepared using citrus peels.

#### 4. Citrus peels derived metallic nanoparticles (MNPs)

The term 'nanoparticle' is derived from the Greek word 'nano' which means 'small or dwarf' and its use as prefix indicates a size 10<sup>-9</sup> or one billionth of a meter equating to 1 nm [45]. In recent years, metal nanoparticles (MNPs) or metallic nanoparticles have originated as a new

terminology in the nanoparticles field. The noble metal such as platinum, gold, and silver have beneficial effects on the health and are utilized for synthesizing nanoparticles and hence, are called metallic nanoparticles [45]. The quality and composition of the biological ingredients used in manufacturing nanoparticles, alternatively referred to as phytosynthesis or biogenic synthesis, are crucial for achieving efficient and environmentally friendly outcomes. The procedure for generating metal oxide nanoparticles requires a reaction between a metal salt solution and an appropriate biological extract. Certain compounds found in biological extracts can serve as capping agents, aiding in the stabilization of nanoparticles and enabling nanofabrication processes [46]. Additionally, biological extracts offer the capacity to reduce the metallic precursor to its zero-valence state. This reduction leads to the stabilization of the precursor and ensures nanoparticle nucleation [47]. The obtained nanoparticles have the potential to enhance various areas, including food, health, the environment, and agriculture, thus supporting the concept of a circular economy. Table 2 presents a compilation of diverse studies and the corresponding findings associated with the research work discussed in the previous paragraph and the subsequent ones. These studies primarily investigated the process of acquiring MNPs, assessing the health impact, and estimating the environmental effects exerted by MNPs prepared from orange peel.

**Table 2**  
Types of MNPs generated from citrus peels and their respective applications.

Fruit scientific name	Common name	Type of MNPs synthesized	Size (nm)	Shape	Applications	Reference
<i>Citrus paradisi</i>	Grapefruit	Copper	56–59	Spherical	73.5% decolorization of dye, Disperse Yellow 125 at dye concentration of 0.01%, copper nanoparticles concentration of 0.05%	[48]
<i>Citrus lemon</i> , <i>Citrus reticulata</i> , and <i>Citrus sinensis</i>	Lemon, tangerine, and orange	Copper	48–76	Rod and spherical	Remarkable zone of inhibition observed against <i>Escherichia coli</i> (ATCC 25922) and <i>Staphylococcus aureus</i> (ATCC 25923); modest zone of inhibition observed against <i>Listeria monocytogenes</i> (ATCC 19115), <i>Clostridium perfringens</i> (ATCC 13124), <i>Streptococcus pneumoniae</i> (ATCC 13883), <i>Moraxella catarrhalis</i> (ATCC 25240), and <i>Pseudomonas aeruginosa</i> (ATCC 27853) strains	[49]
<i>Citrus maxima</i>	Pomelo	Gold	8–25	Spherical	Strong catalytic activity noticed in degrading 4-nitrophenol into 4-aminophenol; excellent antibacterial activity against gram positive (e.g. <i>Staphylococcus aureus</i> ) and gram negative (e.g. <i>Escherichia coli</i> ) bacteria	[50]
<i>Citrus limetta</i> Risso	Sweet lime	Gold	50–80	Irregular	Outstanding antioxidant activity (assessed using DPPH) and catalytic activity signified by reduction of 4-nitrophenol to 4-aminophenol	[51]
<i>Citrus aurantifolia</i>	Bitter orange	Magnetic iron oxide	3 and 10	Orthorhombic	Good anticorrosive properties as well as resistance to abrasion	[52]
<i>Citrus sinensis</i>	Orange	Magnetic iron oxide	20–24	Spherical	Showed antifungal and antibacterial activities against <i>Candida albicans</i> , <i>Streptococcus mutans</i> , <i>Staphylococcus aureus</i> , <i>Bacillus subtilis</i> , <i>Klebsiella pneumoniae</i> , and <i>Escherichia coli</i> ; anti-inflammatory activity; antioxidant activity (assessed using DPPH); decolorization of methylene blue dye	[53]
<i>Citrus paradisi</i>	Grapefruit	Magnetic iron oxide	28–32	Spherical	Antioxidant activity (assessed using DPPH); exceptional decolorization of dyes such as methyl rose (96.65%), methyl orange (89.64%), and methylene blue (80.76%)	[54]
<i>Citrus sinensis</i>	Orange	Magnetic iron oxide	12–13	Core-shell like shape	Functions as a catalyst for production of biodiesel (yield of 98%)	[55]
<i>Citrus sinensis</i>	Orange	Silver	10 and 35	Spherical	Effective in exhibiting antibacterial activity against <i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i> , and <i>Staphylococcus aureus</i>	[56]
<i>Citrus maxima</i>	Pomelo	Silver	4–11	Spherical	Good catalytic activity indicated by degradation of 4-nitrophenol; antibacterial activity against bacteria <i>Escherichia coli</i> , and <i>Staphylococcus aureus</i> ; antifungal activity against fungi <i>Verticillium dahlia</i> ; and antioxidant activity (using and DPPH ABTS)	[57]
<i>Citrus paradisi</i>	Grapefruit	Silver	14	Spherical	Antibacterial activity against <i>Escherichia coli</i> , <i>Klebsiella pneumoniae</i> , and <i>Staphylococcus aureus</i>	[58]
<i>Citrus reticulata</i>	Tangerine	Silver	45	Spherical	Inhibit biocorrosion caused by <i>Desulfurovibrio</i> sp	[59]
<i>Citrus lemon</i> , <i>Citrus reticulata</i> , and <i>Citrus sinensis</i>	Lemon, tangerine, and orange	Silver	5–80	Irregular, spherical, and rod	Effective in exerting antibacterial activity against <i>Escherichia coli</i> and <i>Staphylococcus aureus</i>	[60]
<i>Citrus macroptera</i>	Wild orange	Silver	11	Spherical	Effective in catalyzing reduction of 4-nitrophenol into 4-aminophenol as well as degradation of methylene blue and methyl orange	[61]
<i>Citrus aurantium</i>	Bitter orange	Zinc oxide	276–309	Spherical	Anticancer effects exerted on human breast cancer cells (MDA-MB-231)	[62]

DPPH: 2,2-Diphenyl-1-picrylhydrazyl; ABTS: 2,2'-azino bis(3-ethylbenzothiazoline-6-sulfonic acid).

Recently, Gao et al. [63] examined the impact of different ultrasonic conditions on the properties of orange peels derived gold nanoparticles (AuNPs). These properties include stability, particle size, yield, anti-inflammatory activity, and phenolic encapsulation effectiveness. Their findings displayed that AuNPs produced through ultrasound (AuNPs-U) exhibited stronger anti-inflammatory action (IC<sub>50</sub> value of 82.91 µg/mL in comparison to 157.71 µg/mL), higher yield, and lower particle size of 13.65 nm in contrast to 16.80 nm, as against the AuNPs prepared without ultrasound (AuNPs-NU). HPLC analysis revealed that hesperidin played a crucial role as a reducing agent in the synthesis of AuNPs. Wei et al. [64] used peel extracts of *Citrus maxima* to synthesize iron nanoparticles and reduce the Fe (III) concentration in aqueous solutions. Results from characterization studies have indicated successful synthesis of irregular iron nanoparticles with sizes ranging between 10 and 100 nm. Additionally, the nanoparticles consisted primarily of Fe<sup>0</sup> nanoparticles, enveloped with diverse biomolecules present in the extracts, and served as stabilizing or capping agents. *Citrus sinensis* orange peel-derived magnetic iron oxide nanoparticles not only displayed a reduction in toxicity against the macrophage cell line (ATCC Raw 264.7), but also exhibited antimicrobial properties against *Staphylococcus aureus* bacteria [65]. Stan et al. [66] synthesized magnetic iron oxide nanoparticles from *Citrus lemon* or lemon peel, displaying a strong

capability to remove antibiotics (piperacillin (PIP), tetracycline (TET), erythromycin (ERY), ampicillin (AMP), and tazobactam (TAZ)) from an aqueous medium. Another study conducted by Barbhuiya et al. [67] explained the environmentally friendly synthesis of silver nanoparticles (AgNPs) using pomelo peel waste. The researchers employed an eco-friendly and quick ultrasonic-assisted technique for synthesis. Their findings indicated that nanoparticles produced through green methodology exhibited mainly spherical shapes upon subjecting them to treatment at both high and ambient temperatures. However, upon ultrasonication, the nanoparticles exhibited a cubic shape. Furthermore, X-ray diffraction (XRD) analysis indicated that the crystallite nanoparticle size ranged between 35 and 40 nm. Fourier-transform infrared spectroscopy (FT-IR), zeta potential research, and X-ray spectroscopy (EDX) confirmed that phenolic compounds played the dual function of reducing and capping the metallic ion (Fig. 1). Mustapha et al. [68] efficiently reduced silver ions into AgNPs using secondary metabolites, including flavonoids, alkaloids, saponins, phenols, steroids, and tannins present in the peel extract of *Citrus aurantifolia*. The peel extract of *C. aurantium* was employed by Ringwal et al. [69] to produce AgNPs, which served both as a reducing and capping agent. These AgNPs were effective in degrading methylene blue dye, with an approximate degradation rate of 95.35% within 98 h of exposure. Furthermore, the nanoparticles exhibited 87.34% and 90.09% degradation efficiency for acridine orange and rose bengal dyes, respectively, after a continuous UV absorption period of 4h. In addition, the methyl orange dye exhibited approximately 51% degradation efficiency after solar irradiation exposure for 10h. The synthesized silver nanoparticles (AgNPs) could act as a photocatalyst for the breakdown of harmful dyes. Omran co-workers [70] have reported that the initial cost analysis established the cost-effectiveness of valorised *Citrus reticulum* or mandarin peels into AgNPs, costing roughly around 7.6 USD/g the green synthesized AgNPs having good savings in reference to the global pricing of the

nanoparticles synthesized chemically.

Recently, Rashid et al. [71] discovered that *Citrus limetta* or sweet lime peel produced zinc oxide nanoparticles (ZnONPs) as a nanoprimer, which were effective in eradicating potato tuber slices, exhibiting enhanced performance in brown and soft rot infected slices in comparison to the non-primed ones. Researchers have also suggested that nanoparticles derived from *C. limmeta* peels have the capability to suppress soft and brown rot potato pathogens. Thenmozhi et al. [72] discovered that ZnO NPs produced from peels of *C. limmeta* exhibited antibacterial potential against *Pseudomonas aeruginosa*.

Numerous studies have established that plant-based materials are much more effective than fungi or bacteria for their ability to reduce metal ions, as certain specific plant extracts could serve as coordination agents [30]. Therefore, using plant materials in the synthesis of metallic nanoparticles (MNPs) can offer a feasible substitute approach, which is advantageous for large-scale industrial applications. The synthesis of MNPs from plant-based materials is an eco-friendly alternative that is simple, sustainable, and economical. Furthermore, this strategy is not only effective in reducing the production of waste and harmful compounds but also ascertains a pristine production methodology [30]. Dikshit et al. [73] highlighted specific difficulties encountered during the green synthesis process for the production of MNPs, including comprehensive optimization research on process parameters (temperature, pH, rotational speed, etc.) as well as the reactants (especially plant materials) required for the regulation of MNP size and shape. Optimization of various reaction parameters is required to enhance the stability and yield of MNPs while decreasing the reaction time.

## 5. Citrus peels derived carbon dots (CDs)

Carbon dots (CDs) are quasi spherical in structure having a size less than 10 nm [74]. Carbon atoms in carbon dots have a  $sp^2$  hybridization

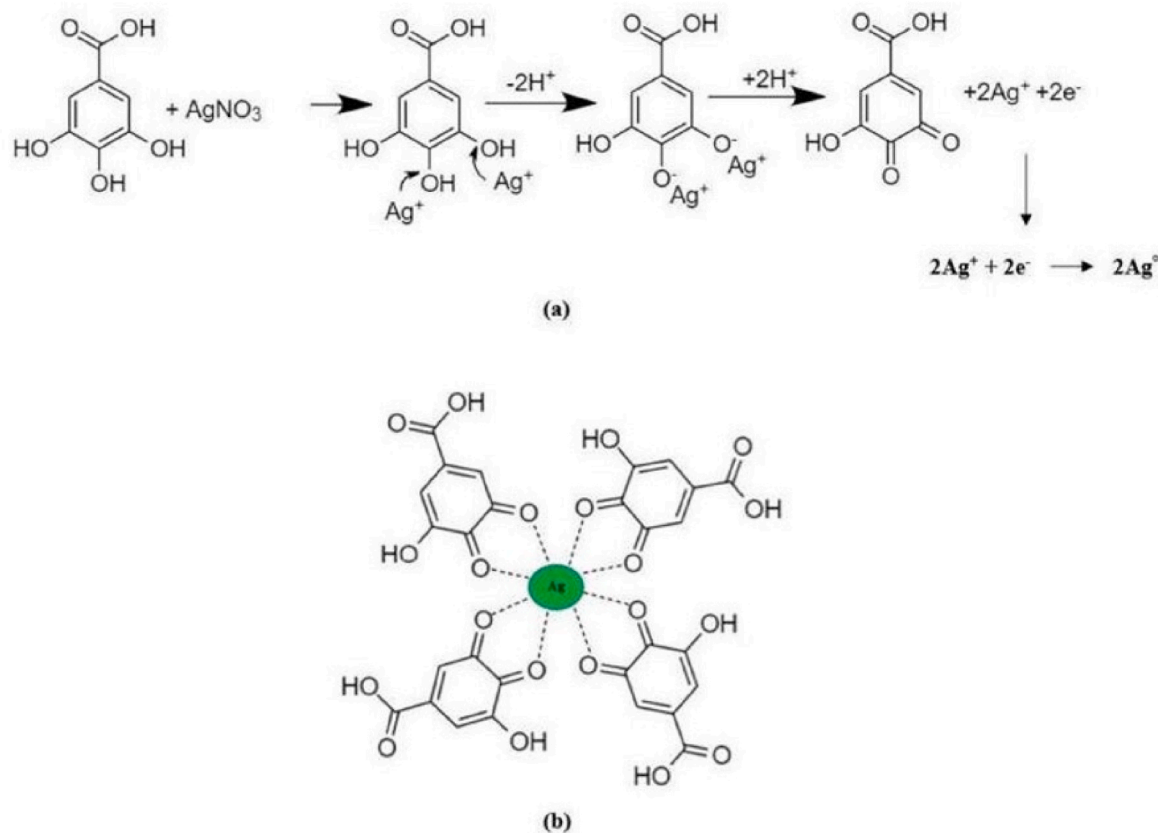


Fig. 1. Reduction of silver nitrite ( $AgNO_3$ ) (a) to silver (Ag) and capping with phenolic compounds (b). [55, License No. 5766390643903].

alongside a few  $sp^3$  centers [74]. CDs have gained significant attention in terms of their exceptional ability to remain stable under light, compatibility with living organisms, low toxicity levels, capacity to dissolve in water, high sensitivity, capability of selective detection of specific substances, efficient light emission ability, large difference between emitted and absorbed light wavelengths, and ability to adjust wavelengths for light emission [75]. Biomass with a considerable heteroatom concentration is regarded as the optimal feedstock for producing carbon dots, as opposed to CDs prepared from synthetic carbon sources, necessitating the introduction of several exogenous heteroatoms [75].

Recently, Jayakumar et al. [76] studied the process of creating carbon quantum dots (LCQDs) derived from peels of dried lemon via hydrothermal synthesis. The prepared LCQDs were linked to polyvinyl alcohol (PVA) to produce functional films. These LCQDs displayed outstanding antibacterial, fluorescent, and antioxidant properties against *Bacillus cereus*, *Salmonella enterica*, *Escherichia coli*, *Staphylococcus aureus* and *Listeria monocytogenes*. The LCQDs were exceptionally compatible with PVA-based films, as validated by FTIR and field emission scanning electron microscopy (FE-SEM). The inclusion of 3% LCQDs in the PVA film significantly enhanced its water vapor and mechanical barrier qualities. In addition, this resulted in improved blocking effects of UVA (99.1%), UVB (99.9%), and UVC (99.9%) radiation. Kundu et al. [77] applied microwave pyrolysis to fabricate water-soluble lemon-peel-derived carbon quantum dots (LP-CQDs) as carbon precursors. The LP-CQDs showed promising results for the detection of tetracycline (TC) antibiotics via the photoluminescence turn-off method (Fig. 2). They exhibited a higher sensitivity to TC and displayed a limit of detection of 50.4 nM, in the nanomolar range. Researchers have utilized a single-step microwave-assisted solvothermal methodology for synthesizing orange peels derived carbon quantum dots (CQDs) [78]. The prepared CQDs showed excellent dispersion in water, chemical stability, and bright blue photoluminescence, with  $1.16 \text{ nm} \pm 0.1$  an average particle size. Their surfaces are composed of carboxylic and amine groups, and certain dopants are extracted from the bio-precursor. Further, studies were conducted to examine the effectiveness of carbon quantum dot-sensitized solar cells (CQDSSC), which were enhanced by utilizing CQDs/ $\text{TiO}_2$  photoanodes, thus resulting in improvement in

photovoltaic parameters as opposed to the semiconductor with no modification. In another study, green pomelo peels were utilized to create CQDs using a single-step hydrothermal process [79]. The produced CQDs could perform the function of a fluorescent probe that could detect  $\text{Fe}^{3+}$  by decreasing the fluorescence intensity. The detection limit for  $\text{Fe}^{3+}$  was  $0.086 \mu\text{M}$ , whereas the linear range of detection varied between  $0.1 \mu\text{M}$  and  $160 \mu\text{M}$ . Additionally, the rate of recovery for  $\text{Fe}^{3+}$  in the aqueous samples ranged from 83.47 to 106.53%. The addition of L-cysteine (L-Cys) reactivated the fluorescence in quenched CQDs, thereby enabling L-Cys detection with a  $0.34 \mu\text{M}$  limit of sensitivity and a  $0.4\text{--}85 \mu\text{M}$  measurable range. The L-Cys recovery rate ranged between 87.08% and 122.74% for the amino acid drinks. Wang et al. [80] synthesized CDs from orange peels using a one-step, environmentally friendly hydrothermal process. These CDs showed intense blue fluorescence, with subsequent modification by employing an ethylenediamine tetraacetic acid (EDTA) ligand. CDs@EDTA displayed greater sensitivity than the CDs for the detection of hexavalent chromium (Cr (VI)) ions, with a detection limit of 10 nM. The prepared CDs@EDTA was verified to be an efficient fluorescence sensor for the detection of Cr (VI) in various water samples. Observations revealed that the recoveries had < a 5% relative standard deviation (RSD), and their values ranged between 92.09% and 104.87%. Also, the fabricated CDs@EDTA/Cr(VI) system was then optimized to act as fluorescence sensor, being capable of detection of ascorbic acid (AA) by switching between "on" and "off" states. The detection limit of  $0.1 \mu\text{M}$  was observed for the system.

The major challenge encountered in CDs generation from biomass lies in yield variability, which can fluctuate between low and high owing to differences in composition [81]. Nonetheless, a limitation of CQDs produced from lemon peels is the difficulty in achieving high quantum yields, as identified in a literature review [77]. The hydrothermal process is considered a sustainable environmentally friendly technology as it requires non-polluting synthetic conditions involving the use of non-toxic materials [30].

## 6. Citrus peels derived biochar

Biochar is a carbon-rich substance generated from organic feedstock

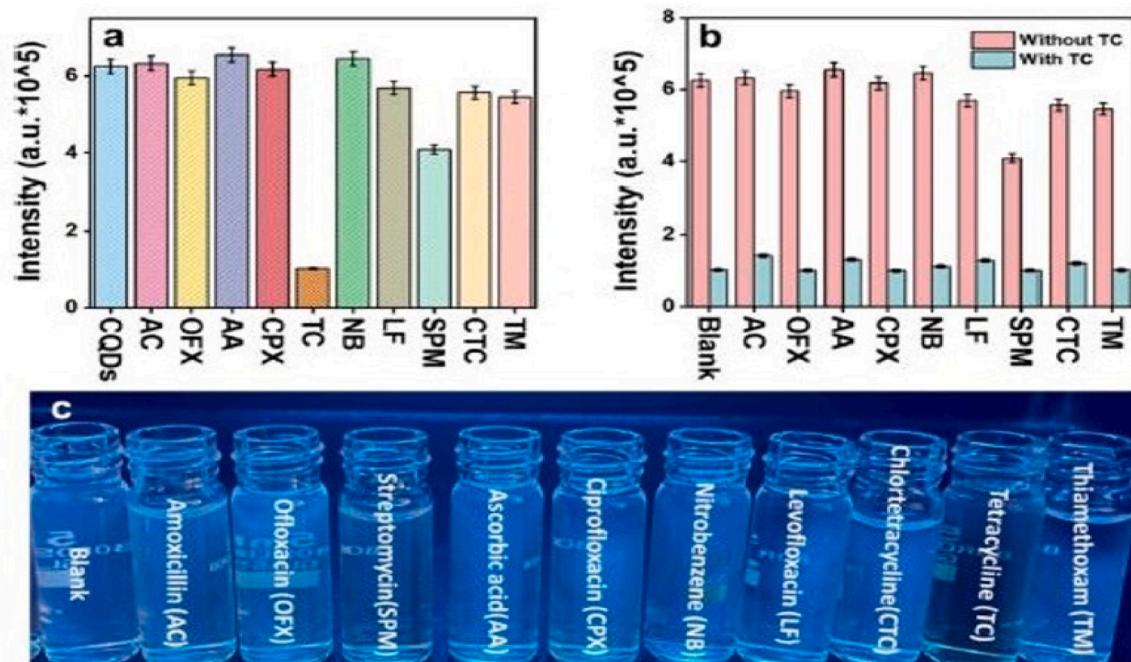


Fig. 2. (a) Selectivity of LP-CQDs towards various antibiotics (b) Interference study with or without TC with different antibiotics (c) Selectivity of LP-CQDs towards various antibiotics under UV light irradiation. [63, Licensed under CC-BY-NC-ND-4.0].

at certain thermal combustion having limited oxygen supply [82]. Mishra and Mohanty [83] documented that biochar principally originates from biomass pyrolysis. Eventually, human activities have resulted in increase of such metal concentrations causing toxicity in the water, posing a serious environmental threat to aquatic ecosystems. However, the shortage of irrigation water has led to the reconsideration of new strategies for wastewater treatment [84]. A number of studies have repeatedly shown that the addition of biochar to wastewater can improve water quality and efficiently remove drug residues and lethal metals from contaminated drinking water [85–88]. The method to manufacture biochar is economically efficient (higher product yields and lower energy loss), ecologically friendly (biomass is regarded as carbon neutral due to emission of carbon dioxide from biomass which is compensated via carbon assimilation occurring while photosynthesis of biomass; it is also reported to have lesser atmospheric adverse effects because it contains lower amounts of nitrogen (N) and sulphur (S), resulting in lower nitrogen oxides (Nox) and sulphur oxides (Sox) emissions as compared to fossil fuel), and efficient for the reuse of waste resources [89]. This approach can expedite the requisite shift toward a carbon-neutral economy [90]. Hence, biochar generated from trash can provide an alternative methodology for managing garbage and recovering resources, thereby helping to reduce the effects of climate change and safeguarding the environment. Table 3 illustrates the efficient removal of toxic metals, pharmaceutical residues, and artificial colors from the aqueous environment via biochar produced from various citrus peels.

To improve the use of biochar-derived adsorbents for CO<sub>2</sub>, researchers have prepared new biochar adsorbents from pomelo peels (Fig. 3). The authors utilized a 2-step process of activation and carbonization with potassium hydroxide (KOH) and diammonium phosphate (NH<sub>4</sub>)<sub>2</sub>HPO<sub>4</sub> as the activator and dopant, respectively. This led to the manufacture of a variety of N, P co-doped pomelo peel-derived biochars (NPBCs), as documented by Xu et al. [99]. The highest-performing NPBC samples achieved the maximum adsorption capacities of CO<sub>2</sub> as 5.74 and 3.41 mmol/g at 273.15 K and 298.15 K temperatures, respectively and 1 bar pressure. The NPBC adsorption capacity was reduced by 9.36% after 10 cycles, indicating its exceptional cyclic stability. Xiao et al. [100] fabricated a new kind of biochar known as PB/NBCs by treating discarded pomelo peels with Prussian blue dye. The biochar was designed to effectively collect ammonia (NH<sub>3</sub>) found in composting gases. Another biochar, PP-500, was developed by carbonization via pyrolysis at 500 °C

using pomelo peel as the raw material. Prussian blue (PB) on the PB/NBC surface tended to increase the quantity of acidic functional groups (AFGs) and improve the availability of active adsorption sites. The findings revealed that the substance contained a large number of mesopores, having 3.82 an average pore diameter. The structure was capable of attaining an outstanding adsorption capacity (152.8 mg/g) for NH<sub>3</sub> at 298 K and 100 kPa, owing to its arrangement. Moreover, the material exhibited rapid adsorption kinetics. The authors believe that the adsorption mechanism of PB/NBC-500-4-4 combines physical and chemical adsorption. The researchers employed 80% sulfuric acid for dehydration and the production of a unique type of biochar derived from discarded mandarin peels. This biochar was further treated with triethylenetetramine (TETA) to create a mandarin biochar-TETA (MBT) complex [101]. This study aimed to assess the effectiveness of biochar, a recently discovered material used in the removal of color, Acid Yellow 11 (AY11) from aqueous solutions. The results revealed that a maximum adsorption capacity (Q<sub>m</sub>) of 384.62 mg/g was determined by MBT. The improvement in positively charged sites produces electrostatic attractive forces in acidic environments, which tends to be the primary mechanism for the adsorption of AY11 dye anions by the MBT adsorption method. Nguyen et al. [102] investigated the effectiveness of pomelo peel-derived iron-coated biochar (PPCI) for the elimination of arsenate As(V) and arsenite As(III) using iron and slow pyrolysis carbonization, respectively. Based on the Langmuir adsorption model, the maximum amount of As (III) adsorbed on PPCI is 11.77 mg/g at pH = 7, whereas the highest amount of As(V) adsorbed on PPCI is 15.28 mg/g at pH = 7. The PPCI adsorption capacity was markedly higher than that of the raw pomelo peel (PP). Results have revealed that the mechanisms of adsorption primarily involved interaction between arsenic (As) and iron (Fe) on the polyphosphoric acid supported clinoptilolite (PPCI) surface. The adsorption process was characterized by inner-sphere complexation of As (III) and As(V) and electrostatic attraction exclusively for As(V). The mechanism of cadmium (Cd) adsorption and its adsorption capacity on orange peel (OP)-derived biochar were assessed by Tran et al. [103] at various pyrolysis temperatures (400, 500, 600, 700, and 800 °C) with heating times of 2 and 6 h. The results demonstrated that altering the heating time and pyrolysis temperature had no effect on the Cd adsorption capacity of the biochar (p > 0.01). Cd showed the highest adsorption capability value of 114.69 mg/g (milligrams per gram). For charcoal, the term used to describe Cd adsorption is chemisorption. Cr<sup>+</sup>-cation

**Table 3**  
The utilization of citrus peels for the production of biochar and its prospective uses.

Fruit scientific name	Common name	Process	Applications	Reference
<i>Citrus limetta</i>	Sweet lemon	Pyrolysis at 350 °C for 1 h	High adsorption capacity of 41.57 mg/g for removal of methylene blue dye	[85]
<i>Citrus sinensis</i> , <i>Citrus lemon</i>	Orange, lemon	Pyrolysis at 300–700 °C for 1 h	The biochar generated at 500 °C temperature exhibited better fuel qualities, with highest values for both carbon content and higher heating value (HHV)	[91]
<i>Citrus aurantium</i>	Bitter orange	Pyrolysis at 400 and 600 °C for 1 h	Used as a probable material for absorption of light in solar absorber coatings	[92]
<i>Citrus sinensis</i>	Orange	Pyrolysis at 200–600 °C for 12 h	Maximum adsorption capacity for sulfamethoxazole and ibuprofen was found out to be 60.90 and 58.12 mg/g, respectively	[86]
<i>Citrus maxima</i>	Pomelo	Pyrolysis at 400 °C for 1 h	Displayed strong attraction towards sulfate ions, with 35.21 mg/g as the maximum adsorption capacity for sulfate	[93]
<i>Citrus maxima</i>	Pomelo	Pyrolysis at 450 °C for 1 h	Displayed methyl orange adsorption at 147.87 mg/g rate for adsorbent	[94]
<i>Citrus limetta</i>	Sweet lemon	Pyrolysis at 350 °C for 3 h	Lead (Pb <sup>2+</sup> ) demonstrated 2840.91 mg/g as the maximal adsorption capacity	[95]
<i>Citrus maxima</i>	Pomelo	Pyrolysis at 400 and 600 °C for 2 h	Adsorption capacity for removal of oxytetracycline is 407.5 mg/g, chlortetracycline is 555.56 mg/g, and tetracycline is 476.19 mg/g	[87]
<i>Citrus sinensis</i>	Orange	Pyrolysis at 300 °C for 2 h	Biochar would exhibit increased catalytic activity, adsorption capacity, and water retention capacity owing to its larger surface area and possibly higher density of active sites	[96]
<i>Citrus limetta</i>	Sweet lemon	Pyrolysis at 450 °C for 1 h	The biochar demonstrated a high adsorption capacity of 100 mg/g for hexavalent chromium (Cr(VI))	[88]
<i>Citrus sinensis</i>	Orange	Pyrolysis at 800 °C for 3 h	The cadmium (Cd <sup>2+</sup> ) and copper (Cu <sup>2+</sup> ) ions were eliminated effectively	[97]
<i>Citrus sinensis</i>	Orange	Pyrolysis at 150–700 °C for 6 h	Exhibits effective absorption capacities for 1-naphthol and naphthalene	[98]

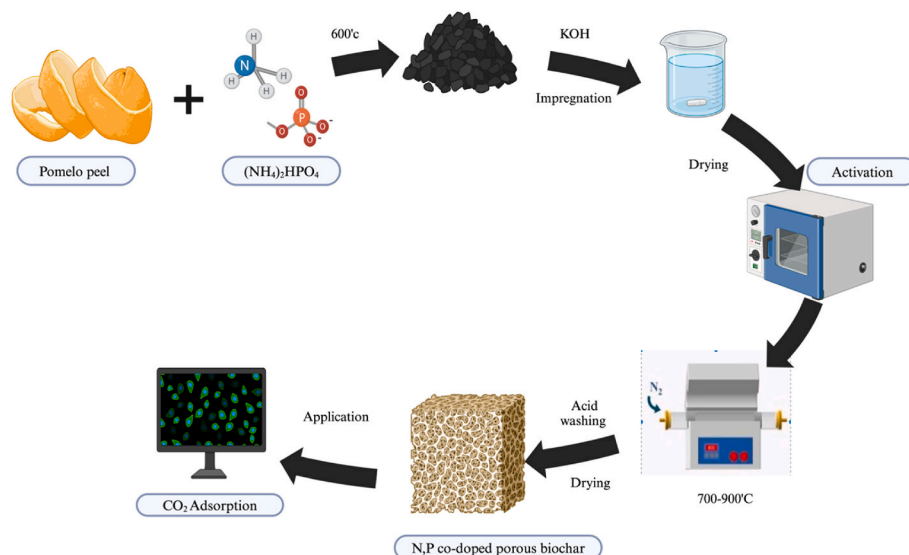


Fig. 3. Pomelo peel-derived biochar schematic presentation. [83, Adapted with license No. 5766391077084].

interactions and surface precipitation have been established as the major adsorption processes. Kalengyo and co-workers [104] have reported that biochar prepared from *Citrus sinensis* L. Osbeck or orange peel was efficient in treating the dye-laden wastewater. This study also maintained that the combined system adsorption/co-digestion/pyrolysis revealed a financially viable scenario, having a payback 7.5 years period for recovering the initial investment of project.

It has been documented by Mishra and Mohanty [83] that biochar produced during pyrolysis lacks adequate surface functional groups and porosity. Therefore, it is necessary to undergo surface functionalization before its efficient use as a strong functional solid for practical applications. Several physicochemical strategies can be employed to boost the surface area and porosity of biochar, consequently expanding its potential applications in nanotubes, energy storage devices, bio-composites, catalysis, environmental protection, and super-capacitors [30].

## 7. Citrus peels derived bio-adsorbent

Adsorption technique can facilitate removal of impurities such as organic, biological, and inorganic compounds [105]. Low cost with stability, non-polluting nature, and high sorptive capacity are the key characteristics essential for an excellent adsorbent. The current research

has focussed on less expensive adsorbents and their associated mechanisms for removal of pollution which further enhances the removal capacity leading up to 99.99% [105]. On the whole, the adsorption process cost can be greatly reduced by using inexpensive as well as easily accessible biological substances, such as biomass, agricultural waste, or microbial cultures [105]. The utilization of biomass waste for creating bio-adsorbents has number of benefits, such as low cost, high efficiency, simplicity in synthesis, sustainability, renewability, high surface area, low toxicity, functional groups, pH tolerance, surface modification, and temperature tolerance [105,106]. The concept of a circular economy has made the use of waste resources more efficient, easier, and reprocessed them so as to attain cleaner production goals, along with treating wastewater [107]. Scholars have been actively engaged in studying the utilization of bio-adsorbents produced from fruit waste for wastewater treatment. These adsorbents have been employed to eliminate various water contaminants, including radioactive materials, oils, organic chemicals, pigments, pharmaceutical waste, and metals causing toxicity [108]. Table 4 summarizes the different uses of bio-adsorbents derived from citrus fruit peels in bioremediation applications.

Eddy et al. [117] created an orange mesocarp-derived mesoporous adsorbent and used it to remove trypan blue from aqueous solutions via adsorption. The prepared samples were analyzed using Energy-dispersive X-ray spectroscopy (EDX) to detect the heteroatoms

Table 4

Utilization of citrus peels for the production of bio-adsorbents and their many uses.

Fruit scientific name	Common name	Drying temperature and time	Applications	Reference
<i>Citrus sinensis</i>	Orange	500 °C, 2 h	Demonstrated outstanding performance, reporting over 95.5% elimination of N-acetyl-para-aminophenol (APAP) after 90 min	[109]
<i>Citrus aurantium</i>	Bitter orange	70 °C, 24 h	Demonstrated the greatest capability to adsorb dye methylene blue, having adsorption capacity of 108.9 m <sup>2</sup> /g	[110]
<i>Citrus sinensis</i>	Orange	80 °C, 12 h	The maximum cadmium (Cd(II)) ion absorption occurred with a contact period of 120 min, having initial metal concentration of 240 mg/L, adsorbent dosage of 0.04 g/L, temperature of 45 °C, and 5.5 pH of solution	[111]
<i>Citrus reticulata</i> L.	Mandarin	100 °C, 24 h	Achieved a remarkable clearance rate for methylene blue (99.77%), 5 mg/L dye concentration at 6.9 pH value proved to be most effective	[112]
<i>Citrus maxima</i>	Pomelo	60 °C, NS	The methylene blue showed 81.7 mg/g adsorption capacity	[113]
<i>Citrus limetta</i>	Sweet lemon	90 °C, 24 h	The maximal adsorption capacity for methylene blue was observed to be 227.3 mg/g	[114]
<i>Citrus sinensis</i>	Orange	100 °C, NS	Demonstrated superior adsorption capabilities as adsorbents for salicylic acid, flurbiprofen, and diclofenac sodium	[115]
<i>Citrus limetta</i>	Sweet lemon	120 °C, 2 h	A maximal efficiency of 95% for removal of Brilliant green dye could be achieved at original concentration of 10 mg/L	[116]

NS: Not specified.

(S, O, and N). Heteroatoms act as entities involved in the creation of competing adsorption locations. The results revealed that the mesoporous bio-adsorbent successfully removed 97.10% of the trypan blue dye. The adsorption capacity displayed a direct relation with the contact time, adsorbent dosage, and concentration, while having an inverse relation with pH. With the intention of getting rid of the colors from water, Rani and Chaudhary [118] have analyzed the activated *Citrus limetta* peel (ACLP) for their potential to adsorb crystal violet and methylene blue. An ACLP dose of just 0.1 g was capable of removing 89.87% crystal violet and 82.77% methylene blue dyes in 120 min and at pH 7, based on the process optimization. Another study by Oyewo et al. [119] investigated the efficiency of orange peel (ORN) nano-adsorbents for the adsorption of cerium ions from simulated water. Their findings revealed that ORN possessed narrow particle sizes (4–50 nm), a larger surface area, and a spherical shape. The carboxyl group present in the structure is mainly responsible for coordinating and removing metal ions. According to the Langmuir isotherm model, the adsorption process adhered to it, with a 45.2 mg/g capacity for ORN. The enhanced performance of ORN can be attributed to its increased surface area and reduced particle size. Januário et al. [120] developed a bio-adsorbent from *Citrus reticulata* peels to absorb safranin orange dye. The findings revealed the highest adsorption capacity (464 mg/g) at 318 K temperature, 0.4 g/L adsorbent concentration, equilibrium time of 120 min, and removal percentage of 84.75%. The suggested primary adsorption mechanisms were  $\pi$ -interactions, electrostatic interactions, and hydrogen bonding (Fig. 4). Furthermore, the reuse of the adsorbent displayed a significant efficacy with an adsorption capacity remaining above 50% after 4 cycles (declining from 77.90 to 41.55 mg/g). The chemical functionalization technique is important in material design because it improves the capacity of the bio-adsorbent to selectively target several chemicals [30]. Further investigations are required to determine the bio-sorbent efficiency derived from different citrus peels, as all peel varieties have unique chemical characteristics and functional groups [24]. At times, it has been observed that the test solution (sample containing substances that are to be eliminated) tends to acquire a brown coloration, which may be ascribed to the extraction of carotenoids from the citrus peel biomass. Carotenoids bind to metal ions causing toxicity present in the test sample and form complexes. The created complex was unable to adsorb onto the biosorbent surface. Consequently, it remains in the solution and causes a color change [121].

## 8. Citrus peels derived biodiesel

The major constituents of biodiesel are alkyl esters of unsaturated and saturated fatty acid, but the composition as well as the fatty acid ester types varies based on the feedstock sources used for production

of biodiesel [122]. Biodiesel has been characterized as a less toxic, inherently biodegradable, oxygenated, along with negligible sulphur content fuel [122]. Biodiesel is a widely acknowledged primary alternative fuel for conventional diesel engines owing to its similar physical characteristics [30]. In 2022, the International Energy Agency (IEA) had issued a warning that feedstock shortages for biodiesel, biojet fuel, and renewable diesel production will be encountered between 2022 and 2027 [123]. This shortage can be related to the availability of animal fats and cooking oil [123]. In the period between 2011 and 2020, the European Union witnessed a rise in the use of environment friendly biofuels produced from recycling of cooking oil, with an increase to 2.53 million tonnes of oil equivalent (Mtoe) from 0.09 Mtoe, as reported by European Court of Auditors [123].

Different physicochemical techniques have been documented for the production of biodiesel, such as trans-esterification, esterification, supercritical fluids, and pyrolysis [124–127]. Scientists are presently exploring additional techniques against the standard approaches to speed up the conversions and produce rapid results, such as ultrasonic, microwave, and plasma-assisted treatments. Owing to the exceptional performance of catalysts, these tactics are therefore being researched. Among the aforementioned cutting-edge technologies, MW-assisted technology has been acknowledged as the best heating method for biodiesel synthesis [128]. Processing after trans-esterification can be streamlined by the incorporation of solid catalysts. Most frequently, catalysts derived from biomass are available as biochars, which aid biomass waste disposal. Biodiesel production can utilize biomass derived from animals and plants either directly or through the implementation of specific changes [129]. Subsequently, the activated carbon derived from the biomass underwent activation via sulfonation. The activated carbon was transformed to possess an expanded surface area, thus allowing greater exposure of the active areas in the biomass and enhancing the catalytic process effectiveness. Table 5 presents a concise outline of the different characteristics of citrus peel-derived biodiesels.

Recently, Oliveira et al. [134] developed a more environmentally friendly and heterogeneous catalyst, referred to as tangerine peel catalyst (TPC), from *Citrus reticulata* Blanco or mandarin peel ash with the intent of producing biodiesel (Fig. 5). The prepared TPC was efficacious in synthesizing biodiesel through the methyl pathway, utilizing used cooking oil and refined soybean oil as the starting ingredients for the biorefinery-based system. Eight different catalysts were produced by heating peel ash to 700, 800, and 900 °C for TPC7, TPC8, and TPC9, respectively. Additionally, mixtures of TPC7, potassium carbonate ( $K_2CO_3$ ), and calcium carbonate ( $CaCO_3$ ) were prepared. Their findings underlined the effectiveness of TPC8 and TPC7 in the production of waste-cooking oil-derived biodiesel, thus enabling an economically viable and sustainable approach. Kumawat and Rohum [135] used

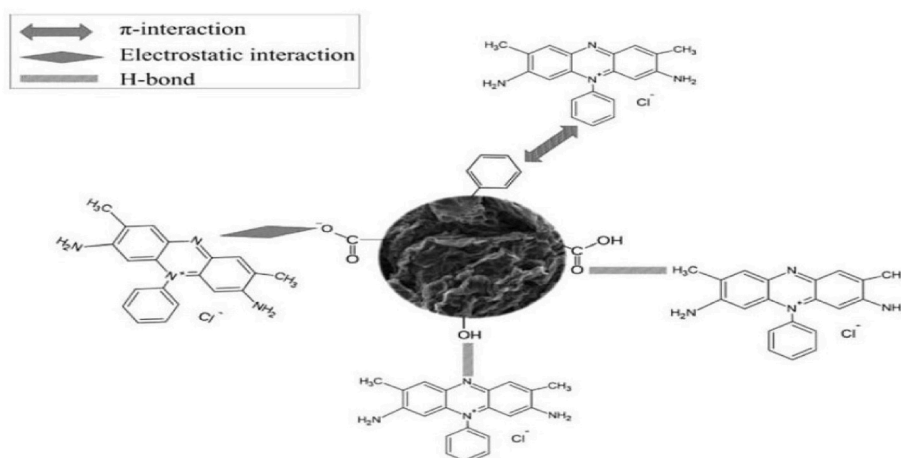
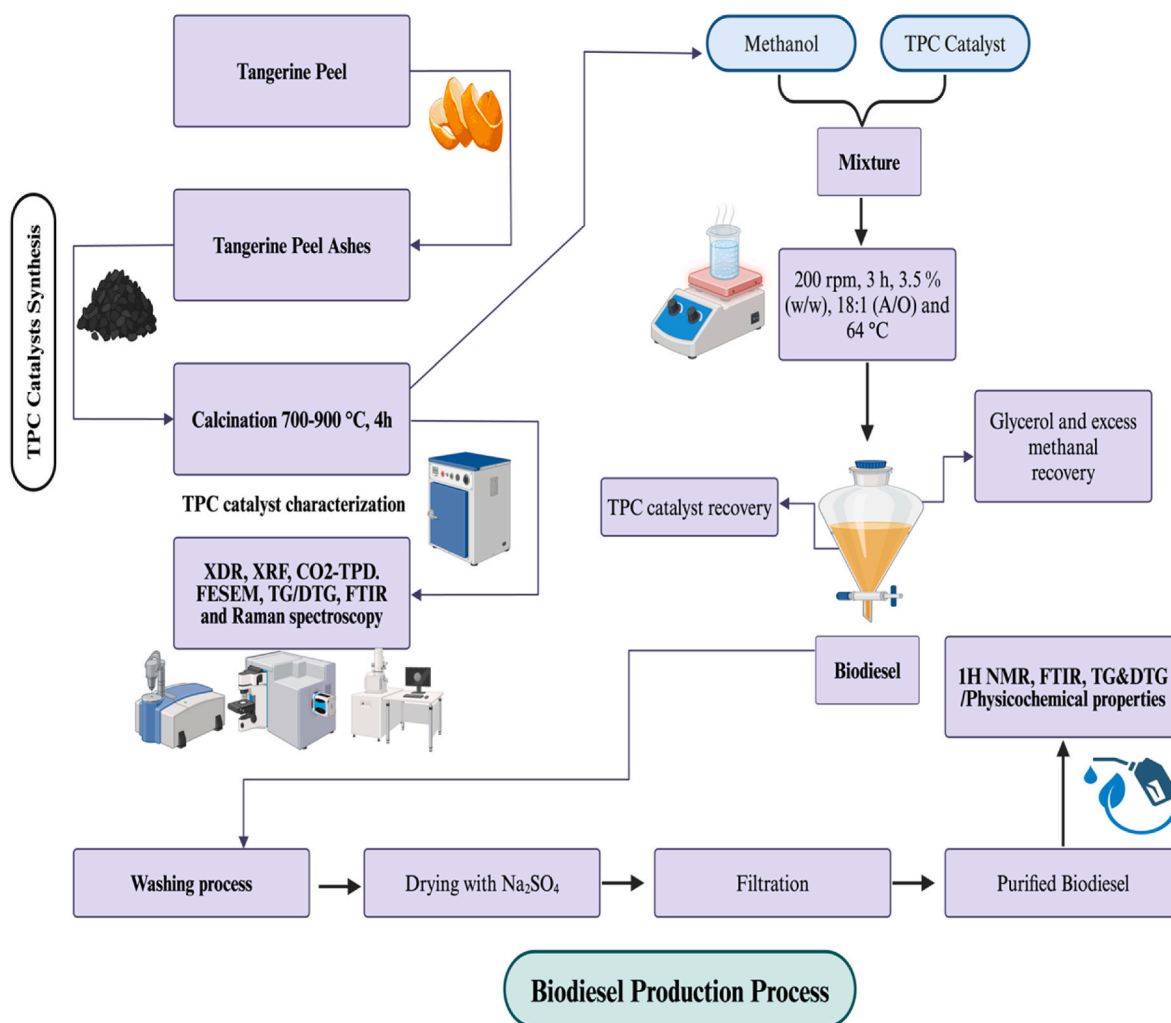


Fig. 4. Mechanism of adsorption of safranin orange (SO) on mandarin peel (MP)-derived bio-adsorbent. [102, License No. 5766391433317].

**Table 5**  
Distinctive attributes of biodiesel produced from citrus peels.

Fruit scientific name	Common name	Density	Kinematic viscosity	Flash point	Fire point	Calorific value	Reference
<i>Citrus sinensis</i>	Orange	872Kg/m <sup>3</sup>	1.9 cSt	84 °C	ND	38.4MJ/kg	[130]
<i>Citrus lemon</i>	Lemon	0.85g/mL	1.06mm <sup>2</sup> /s	327K	337K	41.5MJ/kg	[131]
<i>Citrus sinensis</i>	Orange	0.87 gm/cc	4.8mm <sup>2</sup> /s	140 °C	ND	38887KJ/kg	[132]
<i>Citrus sinensis</i>	Orange	850Kg/m <sup>3</sup>	7.63mm <sup>2</sup> /s	181 °C	188 °C	45.11MJ/kg	[133]

ND: Not determined.



**Fig. 5.** Schematic representation of biodiesel production using tangerine peel as the catalyst. [115, Adapted with license No. 5766400485660].

orange peel as a raw material for the production of carbon-based solid acid catalysts. The catalysts were prepared by treating orange peel with a carbonization-sulfonation reaction, resulting in 1.96 mmol/g density of a sulfonic acid group ( $-\text{SO}_3\text{H}$ ). A "one-pot" synthetic process was employed for the synthesis. The reaction parameters were optimized by employing a 7 wt % catalyst loading relative to the oleic acid (OA), 15:1 methanol to OA molar ratio, 80 °C reaction temperature, and reaction time of 60 min. With an excellent  $96.51 \pm 0.4\%$ , OA was effectively converted to methyl oleate, an important component of biodiesel. In addition, the researchers asserted that the synthesized catalyst exhibited exceptional stability and recyclability when used repeatedly, resulting in a nominal reduction in the biodiesel conversion rate over five catalytic cycles. Rajendran et al. [136] achieved 96.3% biodiesel production using a charcoal-based catalyst derived from *Citrus medica* or citron fruit peel. The optimized experimental reaction parameters included a 1:10 oil (food waste) to methanol molar ratio, 4 wt% catalyst loading, 55 °C

reaction temperature, and reaction duration of 52 min. The results revealed that the prepared catalyst was consistent in maintaining the biodiesel output for four complete cycles. The techno-economic analysis revealed that the yearly plant revenue was estimated to be USD24,140,000 for a 20 year project lifetime, with a payback time of 3.16 years, internal rate of 39.92% return after tax, and net present value of USD55,017,000 at 10.0% interest. Another study by Yadav and Ahmaruzzaman [137] utilized leftover delicious lemons or *Citrus limetta* peels performing the function of as acidic catalysts for the esterification of OA to produce biodiesel. An impressive 96% conversion rate for biodiesel was achieved using optimal conditions, viz 1:20 OA to methanol molar ratio, 5 wt % catalyst loading, 70 °C temperature, and a reaction duration of 3 h. An impressive conversion rate of 87% was achieved for the catalyst in only 1 h, along with the highest conversion rate of almost 96%. The exceptional activity of this catalyst can be attributed to the presence of sulfonic groups and their porous structures. The produced catalyst

exhibited outstanding catalytic efficiency over three cycles.

Recently, there has been tremendous interest in the development of bio-derived catalysts as a possible alternative to traditional chemical catalysts owing to their cost-effectiveness, porosity, eco-friendliness, large surface area, and distinctive features [129]. Bio-derived substances consist of industrial and biological waste and contain abundant minerals, such as calcium and potassium, which can increase the rate of esterification/transesterification [129]. Selvarajoo et al. [91] found that the biomass obtained from dried citrus peels contained higher ash content when pyrolyzed at higher temperatures, further contributing to fouling and slagging issues during combustion.

## 9. Citrus peel derived essential oil (EOs)

Essential oils (EOs) constitute complex mixtures of compounds having low molecular weight and are extracted from plants [138]. Phenylpropanoids and terpenoids are the major components of EOs which provide biological properties and characteristic aroma to them [138]. EOs derived from citrus fruit peels are desirable because of their high oil content found in them [24]. Nevertheless, EOs can occasionally be misleading in terms of addressing the body's fundamental requirements. They are essential because they contain pleasant substances that enhance the unique scent and taste of citrus fruit. EOs are organic extracts obtained from plants and are characterized by their fragrance, nonpolar nature, and volatility. These properties add to their medicinal uses and distinctive odor [24]. Essential oils (EOs) are predominantly obtained from citrus fruit peel. Their processing helps to reduce the quantity of waste generated, as well as the magnitude of environmental pollution. Exploiting citrus EOs as low-cost, natural substitutes for artificial flavoring and preservatives has contributed to the food industry's top priority in ensuring nutritious and safe food. Presence of significant bioactive compounds demonstrating antibacterial activities include linalool, D-limonene,  $\alpha$ -pinene,  $\beta$ -pinene, sabinene,  $\alpha$ -terpineol,  $\beta$ -myrcene and other substances, have been strongly established [24]. Furthermore, these compounds have antioxidative and anticancer properties [24]. In addition, coatings and films prepared from citrus EOs offer a diverse range of applications in numerous industrial food packaging materials. Different techniques are available for the extraction of essential oils (EOs) derived from citrus oranges. Liquid-liquid extraction, solid-liquid extraction, Soxhlet extraction, maceration, infusion, steam distillation, and several other techniques are commonly used extraction methods [24]. The conventional approach for obtaining EOs is primarily utilized in cold-pressed oil extraction. However, these methods require a longer duration and larger amount of energy. These approaches also require higher temperatures, which may potentially degenerate heat-sensitive constituents [139]. Occasionally, the traditional strategy requires the addition of harmful solvents to extract the oil, which is not suitable for food applications [139]. Various sectors have widely used advanced techniques, including microwave-assisted extraction (MAE), accelerated solvent extraction (ASE), supercritical fluid extraction (SFE), and ultrasonic-assisted extraction (UAE) [140]. Table 6 provides a concise outline of the limited studies conducted on essential oils extracted from citrus peels, along with information on the extraction process and the resultant yield.

Anwar et al. [149] used petroleum ether as a solvent for the extraction of EOs from orange peel using a Soxhlet system. The obtained oil was brownish yellow in color and emitted a tangy odor. The oil was insoluble in water, had 0.778 g/cm<sup>3</sup> of density and specific gravity of 0.843 g/cm. It shows significant antibacterial potential against *Escherichia coli*, antileishmanial effects, and antifungal properties against *Aspergillus flavus*. The EO obtained from bitter orange or *Citrus aurantifolia* peels was extracted using a hydrodistillation process [150]. The findings showed that the extraction procedure closely adhered to the simultaneous diffusion and washing model, particularly non-stationary diffusion modelling. The optimum extraction conditions for attaining the highest yield included a 3:1 mL/g water and materials ratio, 204 W heating capacity, and 60 min extraction time. Under ideal conditions, EOs were produced with a 3.9% (v/w) yield and evaluated for their composition by GC-MS analysis. The major components of the EOs from lemon peel were primarily  $\gamma$ -terpinene (12.356%) and limonene (62.17%). Arafat et al. [151] extracted EO from sweet lime peels using the vacuum-assisted solvent-free microwave extraction (VAFME) technique. The analysis revealed the presence of 49 diverse compounds in the EO of sweet lime peel. Among these compounds, limonene comprised the largest proportion (43.47%). In addition, the peels were subjected to ultrasonic pretreatment before microwave extraction. Extending the treatment time to 90 min resulted in an increase in the essential oil yield from 0.84% to 1.06% with ultrasonic pretreatment. The increase in yield was 37.66% greater than that obtained with VAFME treatment for 90 min. Hou et al. [152] devised a hydrodistillation technique for EO extraction from mandarin peels. The findings revealed that the oil yield exceeded 3%. Approximately 53 compounds were extracted from citrus essential oils using GC-MS analysis. Terpenes constituted 71.2% of all components, with d-limonene forming the largest constituent, amounting to 58.9%. Citrus essential oil exhibited significant antibacterial effects against *Cutibacterium acnes* and some common pathogens, including *Escherichia coli*, *Staphylococcus aureus* and *Bacillus subtilis*. Song et al. [153] employed microwave irradiation for the extraction of EOs from citrus peels (disclosure of specific citrus species not made by the authors). Their findings suggested that, with the use of 450 W microwave power, a liquid product with 29.22% yield was obtained, of which 37.82% constituted limonene. Limonene production efficiency was measured as yield per unit of energy usage and was estimated to be 18.6-fold greater for microwave heating compared to traditional heating techniques. Ortiz-Sanchez [154] have claimed that production of EOs along with other orange peel waste components for biorefinery project requisites orange juice industry to produce a minimum of 480 tonnes a day for consideration as reasonable and feasible biorefinery projects.

MAE may or may not require a solvent for extraction. However, in the case of dry extraction, the water present in the sample serves as the solvent, resulting in cell lysis [24]. Solvent-free MAE is mainly employed to extract antioxidant compounds and EOs from plant materials [24]. This technique is faster than supercritical fluid extraction and pressurized liquid extraction [24]. Mahato et al. [155] suggested that one of the major practical challenges in extraction is the probable interactions between the proteins present in food products and the active volatile components in EOs, which tend to destabilize EOs and result in the

**Table 6**  
Essential oil derived from citrus peels.

Fruit scientific name	Common name	Extraction method	Yield	Reference
<i>Citrus reticulata</i>	Mandarin	Supercritical fluid extraction	1.57%	[141]
<i>Citrus sinensis</i>	Orange	Hydro-distillation	1.03%	[142]
<i>Citrus sinensis</i>	Orange	Microwave hydrodiffusion and gravity (MHG) and steam distillation	4.22% and 4.16%	[143]
<i>Citrus grandis</i>	Pomelo	Solvent-free microwave extraction (SFME)	25.3%	[144]
<i>Citrus paradisi</i>	Grapefruit	Solvent-free microwave extraction (SFME)	0.44%	[145]
<i>Citrus reticulata</i>	Mandarin	Hydro-distillation and cold pressing	4.53–4.93% and 4.46–4.86%	[146]
<i>Citrus sinensis</i>	Orange	Steam distillation	2.4ml/100g	[147]
<i>Citrus grandis</i>	Pomelo	Hydro-distillation	4.58–4.68%	[148]

production of newer, possibly undesirable compounds. Encapsulation of essential oils inside an appropriate biodegradable shell, with the capability to regulate active chemical release, can offer a potential solution to the current challenge. This can not only decrease EOs instability, that is, their propensity to react with the protein substrate, but also help maintain the antimicrobial effects through regulation of their release [155].

### 10. Enrichment applications of citrus peels in food

Technological advancements have assisted in the mixing of natural additives and novel nutrient sources, leading to improved functionality and the utilization of numerous by-products [156]. The concept of a circular economy has proven effective in the areas of innovative nutritional sources, displaying comparable or even better quality than traditional alternatives. It finds use owing to its ability to integrate the necessity for wholesome food clubbed with environment-friendly production methodologies [156]. An optimal diet must contain a comprehensive variety of macronutrients and micronutrients necessary to fulfil human nutritional requirements. Food enrichment is projected as an intervention approach in regions with a significant incidence of micronutrient deficiencies, providing a method for tackling this problem [157]. Fortification of processed foods has proven to be an effective method for addressing and diminishing the risk of micronutrient insufficiency in populations. Dairy products and cereals are commonly used for fortification because of their compatibility with the diets of children

and their extensive availability [157]. Agro-industrial waste can be considered a realistic and viable source of raw materials and fuel for biorefineries. By-products also play a critical role in valorisation and profit creation in different industries such as food, pharmaceuticals, nutraceuticals, cosmetics, animal feed, and chemicals [158]. Liu et al. [159] investigated several approaches to the management of food waste. Enzymolysis, hydrolysis, chemical extraction, grinding, anaerobic digestion, supercritical fluid extraction with CO<sub>2</sub>, and pyrolysis are among the techniques used for this purpose. The fruit processing industry is presently examining novel approaches for efficient waste management and their employment in an environmentally friendly manner to manufacture diverse products, including purees, juices, jams, cereals, yogurts, snacks, and canned fruit [158]. Peels of citrus and other citrus by-products have been established as potential sources of dietary fiber and antioxidants, which expands their application in the food industry as a nutrient-rich food choice [160]. Fig. 6 provides a comprehensive overview of the advances made in the production of different food products with the help of citrus peels, including dietary fiber, powder, and essential oils.

Citrus peel bitterness requires certain chemical treatments, and this characteristic presents a major problem because of the requirement for expensive solvents and equipment. Another challenge is to ensure the stability of natural chemicals extracted from citrus fruits for their potential commercial applications in the food sector. Therefore, a number of studies have focused on processes involving encapsulation of bioactive compounds, with nano-encapsulation paving the way for future

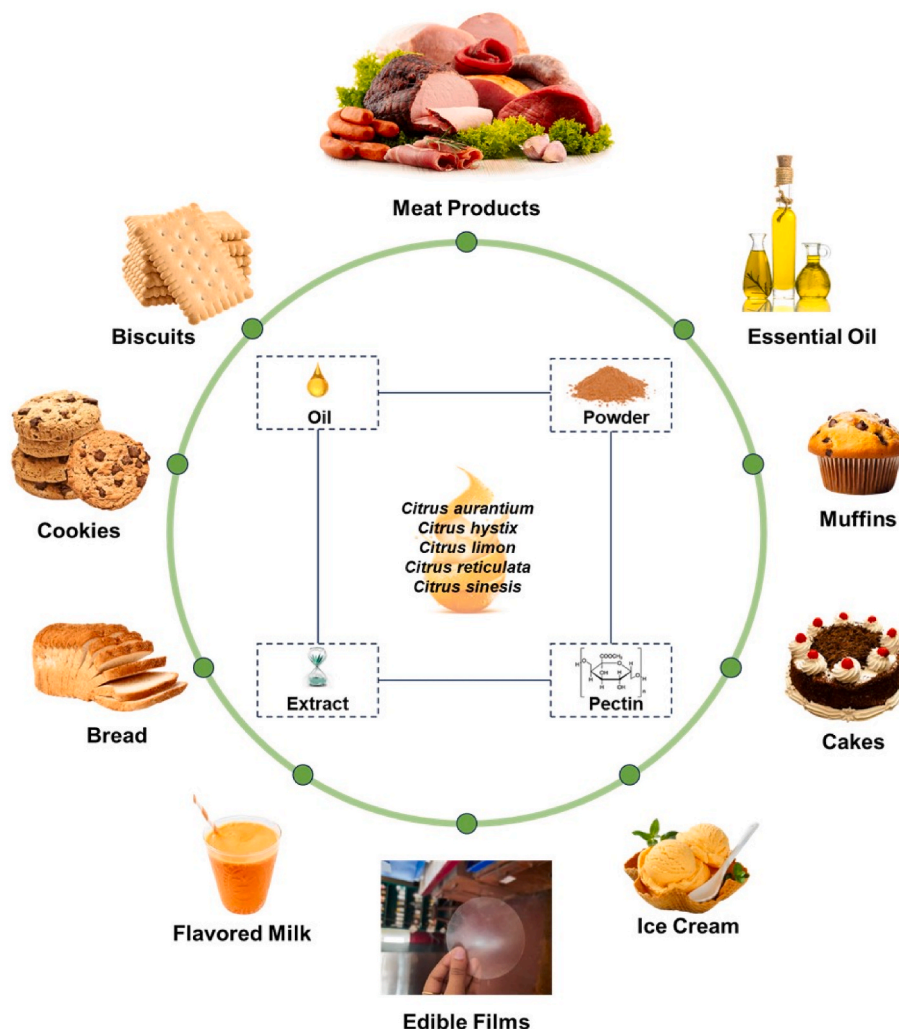


Fig. 6. Various functional foods are produced using citrus peels.

research [161]. However, with technological advances, a dire need to focus on research to put forward industrial applications, with a major focus on intelligently producing functional food and custom-made diets through 3D food printing (3DFP) processes. Thus, bioactive pigments and compounds derived from citrus peel can be efficiently utilized to develop a variety of 3DFP inks [161].

### 10.1. Cereal-based food

Meals prepared from cereals, such as cakes, muffins, bread, and cookies (Fig. 6), are an essential component of our daily dietary requirements because they contain significant quantities of biomolecules, including carbs and proteins. However, they lack fiber, minerals, phytochemicals, vitamins, or other essential micronutrients. The addition of useful elements to basic health and nutrition has been determined by the increasing consumer demand for nutrition-enriched food items [158]. The use of citrus fruit peels in cereal-derived food products serves as a functional ingredient, mostly in powder form, to provide dietary fiber (Table 7). Khaleel et al. [174] studied the *Citrus reticulata* or kinnow peel powder's (KPP) effect on overall muffin quality. The value addition of KPP was achieved by the creation of muffins, wherein refined wheat flour was partially substituted with KPP at different percentages (5, 10, 15, and 20%). An elevated KPP concentration in the muffins led to a reduction in color characteristics, volume, and an increase in hardness. The maximum desirability was observed at the 5% replacement level. Sethi et al. [175] examined the muffins for their phytonutrient levels, antioxidant capacity, and consumer acceptance of kinnow peel enrichment. The study showed that muffins supplemented with 2% candied citrus peel were highly satisfactory, demonstrating enhanced levels of dietary fiber (8.26%), protein (12.70%), total minerals (1.86%), flavonoid content (96.31  $\mu\text{mole Trolox}$  per 100 g), and phenols (88.12 mg per 100 g). Notably, these improvements were perceived without significant changes in the total caloric value or mouthfeel. Citrus peel addition improved the antioxidant content (flavonoids and phenols) of the modified muffins. Recently, Rafiq et al. [176] examined the nutritional and sensory characteristics of soup sticks enriched with freeze-dried kinnow peel powder (FDKPP). Their findings revealed a considerable increase in ash content, breaking strength, viscoelasticity, yellowness, storage stability, and baking quality when the FDKPP content of wheat flour was increased from 0 to 9%. However, a decrease in  $a^*$  (redness),  $L^*$  (lightness), pasting parameters, crude protein, crude fat, and moisture values was observed. Sensory evaluation showed that higher replacement levels had a favorable influence on scent strength and color, but had an adverse effect on taste. Mandarin peels (MP), lemon peels (LP), and orange peels (OP) were utilized and analyzed to prepare functional pasta and cookies, as explained by Hadeer et al. [177]. Sensory evaluation indicated that cookies with 5, 10, and 15% OP fortification were statistically acceptable, whereas the 10% concentration was significantly superior to the control group. The addition of MP and OP to the cookies resulted in increased thickness compared to that of the control. Nevertheless, pasta supplemented with 5% OP was determined to be the most palatable, along with a significant enhancement in the weight percentage as well as the residue amount that remained in boiling water, in contrast to the control. In another study, El-Beltagi et al. [178] discovered that replacement of wheat flour with 10% orange peel powder in sponge cake resulted in the highest concentrations of flavonoid and total phenolic compounds, as well as improved antioxidant activity, in contrast to the un-supplemented regular cake.

### 10.2. Meat-based food

In a recent study by Xu et al. [179], deep eutectic solvents (DESS) were utilized for the extraction of orange peels. Additional studies have been conducted by the research group to investigate the inhibitory effects of choline chloride-based DES extract on the development of bound and free heterocyclic amines (HAs) and advanced glycation end

products (AGEs) in roast pork patties. The results revealed that the neutralization of free radicals, including the extracts of choline chloride-derived deep eutectic solvent (DES), particularly the carbamide and choline chloride-based DES extract, can significantly reduce the oxidation of proteins and lipids. This strategy has proven to be the most effective in reducing the production of advanced glycation end products (AGEs) and harmful aldehydes (HAs), resulting in noticeable decreases in protein-bound and free HAs of 11.5–66.5% and 19.1–68.3%, respectively. Furthermore, a 30.5–39.8% reduction in protein-bound AGEs and a 50.3%–50.8% reduction in unbound AGEs were observed, in contrast to the control. A study conducted by Baioumy and Abdelmaksoud [180] examined the effects (OA) effects on the quality attributes of low-fat-containing beef burgers. These results indicated that the inclusion of OA improved the sensory quality characteristics of beef burgers. The supplemented burger patties had a better pH, water retention capacity, nutritional value, and cooking loss percentage. Additionally, the replacement of animal fat with OA in the recipe led to a reduced calorie content in the treated samples. Sharma et al. [181] investigated the effect of *Citrus limetta* or mosambi peel extract (MPE) on tilapia surimi at various concentrations (ranging between 0.20% and 1.20%, w/w) and its gelling attributes were tested. When the MPE concentration increased to 0.60%, the gel strength, breaking force, and other textural features improved significantly ( $p < 0.05$ ). Conversely, the patterns of the sulfhydryl and free amino acid levels were reversed. By promoting non-covalent contacts, such as hydrophobic and hydrogen interactions, and the formation of  $\beta$ -sheets, MPE improved the gel structure. Compared to gels lacking MPE, this improved cross-linking between proteins and phenolic compounds strengthens the gel network. In addition, MPE addition at an ideal concentration of 0.60 percent resulted in a compact, well-organized, and uniform microstructure. Because of the effective obstruction of water flow inside the network through the microstructure, the water retention and strength of the gel were enhanced. Nishad et al. [182] reported that *Citrus paradisi* or grapefruit peel extract (CP) and nutmeg extract (NM), alone or in combination, can enhance the NM-CP NM-CP-containing meat balls. Compared with the NM and CP separate extracts, the binary mixture (NM-CP) with a 1% concentration had a larger inhibitory effect on lipid oxidation. Further validation of the efficacy of NM-CP in extending the shelf life of frozen meat came from the evaluation of color, sensory characteristics, and flavor. Dua et al. [183] investigated the effect of lemon peel extract on the storage quality and oxidative stability of Tabak-Maz, a well-known traditional meat product prepared from fried mutton rib. The products were prepared and treated with lemon peel extract at three concentrations (0.5, 1, and 1.5%). They were then placed in low-density polyethylene pouches and assessed for their lipid stability and storage quality. The evaluation was performed at lower temperatures in a refrigerated environment ( $4 \pm 1$  °C). The results revealed that the lipid stability of the goods was significantly influenced by the addition of lemon peel extract. Throughout the storage period, the treated products invariably showed significantly decreased thiobarbituric acid-reactive compound (TBARS) and free fatty acid (FFA) levels ( $p < 0.05$ ). A significant influence ( $p < 0.05$ ) on the microbiological characteristics of the samples was also observed. During the total storage time, the lemon peel extract-treated samples demonstrated a significant ( $p < 0.05$ ) reduction in yeast and mold counts, total plate count, and psychrophilic count.

### 10.3. Milk-based food

Jalilzadeh-Afshari and Fadaei [184] examined the effect of bitter orange peel extract at three different doses (0.025, 0.050, and 0.075% w/v) on various flavored milk attributes throughout a ten-day storage period at 4 °C. Their findings showed that increasing the peel extract concentration resulted in an increase in antioxidant activity, total polyphenol content, and viscosity. Concurrently, it led to a reduced overall count of microorganisms and an improvement in the sensory

**Table 7**  
Food products made from cereal and citrus peels, and their quality characteristics.

Product developed	Type of citrus peels used	Quantity added	Product quality	Reference
Biscuits	Fingered citron ( <i>Citrus medica</i> L.) powder	3% and 5%	The statistical sensory evaluation study reported no significant change in the look and flavour attributes of peel powder fortified biscuits, at 3 and 5% concentration	[162]
	Lemon ( <i>Citrus lemon</i> ) powder	1%	The dried lemon peel powder (dried at 65 °C temperature) derived biscuits were most acceptable (top rated) in terms of the sensory aspects	[163]
	Lemon ( <i>Citrus lemon</i> ) powder	1%, 3%, 5%, 7%, and 9%	The biscuits prepared by incorporating 3% levels received best score with respect to the overall acceptability (8.66) among all treatment groups, wherein the value was closest to the control (9.0)	[164]
Bread	Shatian pomelo ( <i>Citrus maxima</i> Burm.) insoluble dietary fibre (IDF)	5–20%	On comparing to control group, the PP-IDF containing bread showed enhancement in moisture rate with 3.50–6.80% value after 7 days; addition of PP-IDF also slowed down the bread staling process; sensory assessment revealed improvement in the bread's taste when the PP-IDF level was between 5% and 10%	[165]
	Kinnow ( <i>Citrus reticulata</i> ) powder	1%, 2%, and 3%	The addition of kinnow peel powder (KPP) at 2% concentration improved the sensory attributes of bread, thus enhancing its acceptability; principal component analysis showed that bread containing 2% KPP had better functional attributes	[166]
	Mandarin ( <i>Citrus reticulata</i> Blanco) powder	2%, 4%, and 6%	The inclusion of peel powder at 6% yielded the best overall acceptance	[167]
Cookies	Kinnow ( <i>Citrus reticulata</i> ) dietary fibre	5%, 10%, and 15%	Created cookies that showcased favorable nutritional, textural, and sensory characteristics, resulting in 7.15–7.84 overall acceptability rating range	[168]
	Sweet lemon ( <i>Citrus limetta</i> ) powder	4–12%	The inclusion of peel powder resulted in augmentating the hardness and thickness of cookies, escorted by a decrease in the spread ratio and breadth of cookies on increasing the peel powder levels; the peel powder addition also improved the content of dietary fiber in the cookies	[169]
Cake	Orange ( <i>Citrus sinensis</i> ) powder	5g	The findings signified that the average overall acceptability ratings of the supplemented cake shifted to "slight liking" category	[170]
	Mandarin ( <i>Citrus reticulata</i> Blanco) powder	10g	The peel powder included cake possessed high crude proteins concentration and displayed enhanced color, whereas a modest decrease in sensory characteristics was observed	[171]
Chin-chin	Orange ( <i>Citrus sinensis</i> ) powder	5%	The analysis of proximate composition of chin-chin displayed a statistically significant ( $p < .05$ ) increase in moisture content (5.05–7.59%), protein (10.34–19.15%), ash (1.50–5.42%), fiber content (2.68–6.01%), and fat (13.84–20.34%); no significant variation in the energy content of the samples	[172]
Spaghetti	Orange ( <i>Citrus sinensis</i> ) powder	5%, 10%, and 15	The findings showed that elevating the orange peels powder quantity resulted in a rise in ash content and dietary fiber, while decreasing calorie content; in addition, the cooking quality aspects were generally reduced as the orange peels powder level was enhanced, with the exception in the swelling index, exhibiting an increase	[173]

attributes of flavored milk ( $p < 0.05$ ). The flavored milk sample containing 0.075% peel extract was considered the most efficient therapy. Maqbool et al. [185] assessed the effects of sweet lime peel powder (SLPP) on the longevity and quality of butter stored for different durations. Butter was subjected to SLPP treatment at concentrations of 1.5, 3, 4.5, and 6%. Samples containing 6% SLPP exhibited elevated phenolic and DPPH levels. Adil et al. [186] developed frozen yogurt with high dietary fiber and  $\beta$ -carotene content by the addition of orange peel components. The appropriateness of 2 orange peel types—orange peel powder (OPP) and candied orange peel (COP) as additives to improve the flavor of frozen yogurt was determined. The compounds OPP and COP were included in the mixtures at 8.0% and 2.5% wt concentrations, respectively, to improve the flavor. The 2.5% OPP concentration showed more favorable results as compared to 8.0% COP concentration, thus proving to be a valuable ingredient in producing 'medium-fat orange frozen yogurt. The product exhibited a better overall sensory rating than other samples. This frozen yoghurt demonstrated a 37.20% increase in  $\beta$ -carotene content as well as a 24% increase in dietary fiber content compared to the control samples. Citrus peels, obtained from bitter oranges, lemons, and sweet oranges, have been indicated by Fathy and teammates [187] to improve the viability of probiotic starter cultures, such as *Streptococcus thermophilus*, *Bifidobacterium* sp., and *Lactobacillus acidophilus* in symbiotic yoghurt fermented through *Acidophilus-bifidus-thermophilus* (ABT), even under refrigeration. In comparison to the control samples lacking citrus peel, it was observed that in ABT symbiotic yogurt, the antioxidant properties were enhanced by the addition of citrus peels.

A study carried out by Ademosun et al. [188] suggested feeding rats with ice cream at different citrus blend amounts, specifically shaddock and orange, for a period of 28 days. The study documented that feeding ice cream containing citrus peels raised antioxidant levels in heart and liver tissues and significantly increased high-density lipoprotein levels

in the blood. Furthermore, a decrease in the blood levels of glycemic index, triglycerides, total cholesterol, and low-density lipoprotein in comparison to rats fed commercial ice cream was observed. A study has established that the incorporation of ice creams prepared by combining shaddock and orange peels into the diet can be favorable for glycemic index control, weight loss, lipid-related disorder treatment, and avoidance of heart and liver issues pertaining to oxidative stress.

#### 10.4. Edible films/coatings

Composite films and coatings, which possess bioactive characteristics, such as antibacterial and antioxidant effects, have been progressively utilized in the food packaging industry. Bioactive packaging materials can potentially improve the safety and quality of food products. The films or coatings act by inhibiting the growth of hazardous microbes and slowing down oxidative reactions that could ultimately result in the degradation of food quality [30]. Package films and coatings derived from bio-based substances containing bioactive components, including antimicrobial peptides, plant extracts, and essential oils, exemplify active packaging materials. Depending on their specific functions, bioactive agents have been categorized into antioxidant packaging coatings/films, antibacterial packaging coatings/films, and other active packaging substances. Recently, citrus peels have been analyzed for their potential use in enhancing functional films and edible coatings. This includes the extraction of pectin, bioactive components, and essential oils from citrus peel (Table 8). These films contain bioactive compounds that act as natural additives, thus exhibiting mechanical, physical, functional, structural, and barrier properties [197–201].

A biodegradable film was created by the addition of SLPP as a filler and using starch and polyvinyl alcohol (PVOH) as the matrix of the film [199]. Nine composite films were generated using variable amounts of polyvinyl alcohol (PVOH), starch, and SLPP via a solution casting

process. The results revealed that the film prepared with a 1.5:1.5:0 ratio of SLPP:PVOH:starch possessed higher qualities than all other films. Amongst the various films, the ideal one displayed a  $36.67 \pm 0.2\%$  moisture content,  $85.09 \pm 0.20\%$  solubility,  $2.54 \pm 0.02$  (10–6 g/pa h m) water vapor permeability,  $1.98 \pm 0.02$  transparency,  $509.32 \pm 0.53$  kPa tensile strength, and  $11.31 \pm 0.05\%$  elongation at break. Asfaw et al. [197] created a pectin-derived edible film with the help of *Citrus medica* or citron peel and rendered it flexible by the addition of glycerol. The study incorporated a range of pectin concentrations, with a 5 g upper limit and a 3 g lower limit. Similarly, the glycerol concentration varied between 15 and 25%. The combined effect of pectin and glycerol concentrations on edible film properties had a significant impact on the overall characteristics. The pectin in the film had a beneficial influence on the opacity and tensile strength. However, they exerted a detrimental effect on the elongation at break and elastic modulus. The elastic modulus and tensile strength of the film were adversely affected by the glycerol proportion. An increase in pectin concentration caused a reduction in biofilm opacity. However, the glycerol present in the film had no significant impact on the opacity. Based on the numerical optimization, it was found that the addition of 4 g pectin and 20% glycerol resulted in the creation of a see-through and robust edible film. In another study, active films were prepared by mixing 0.04% (w/v) maltodextrin-encapsulated lemon peel extract (MD-LPE) along with grapefruit peel methanolic extract (GFPE) containing grapefruit pectin (GFPe) matrix at 3% w/v concentration. Khalil et al. [198] reported that the procedure required 25% w/w polyethylene glycol 400 (PEG400) as a plasticizer for the production of films. The tensile strength, water vapor, UV barrier, and heat resistance qualities, in addition to the soil biodegradability, were significantly enhanced by the addition of MD-LPE capsules and GFPE to produce transparent flexible films. These improvements were observed in comparison to commercially available citrus pectic films. The application of optimal active films on intentionally infected cherry tomatoes effectively inhibited *Escherichia coli* O157:H7 growth by approximately 1.6 log units during refrigerated storage for 6 days. Meydanju et al. [200] designed a biodegradable film from the discarded peels of sour lemons. The film prepared from lemon peel powder (LPP) was enhanced by incorporating TiO<sub>2</sub>-Ag nanoparticles and xanthan gum (XG), resulting in the fabrication of an LPP/XG/TiO<sub>2</sub>-Ag film. Their findings reflected the inclusion

of XG, resulting in heightened viscosity, index of the samples, and moisture content. In contrast, the moisture content and index decreased with the addition of TiO<sub>2</sub>-Ag. The amount of XG decreased slightly as it increased. Similarly, an increase in the TiO<sub>2</sub>-Ag content was attributed to an increase in the yellowness. The inclusion of nanoparticles and gum resulted in a slight increase in the antioxidant potential. When TiO<sub>2</sub>-Ag and xanthan gum were added, the Young's modulus and tensile strength of the film significantly increased, but the water vapor permeability (WVP) and solubility decreased ( $p < 0.05$ ). Jridi et al. [201] used gray triggerfish skin to fabricate gelatin films composed of phenolic compounds obtained from *Citrus sinensis* or blood orange peel. These films could be utilized as alternatives to synthetic packaging films. The results demonstrated that the use of fresh orange peel extract (FOPE) changed the thermal and mechanical characteristics of the gelatin films, leading to improved texture flexibility compared to the film with no modification. This impact could be attributed to the interactions between the gelatin chains and phenolic components in the extract. The films containing FOPE exhibited better antioxidant capabilities than control films.

## 11. Strength and limitations

The current review stands out owing to its novelty along with a comprehensive approach, which is effectively consolidating wide array of applications wherein citrus peels have been utilized efficiently. The foremost key strength lies on the detail aspects of polyphenols found in citrus. Secondly, we have successfully explained synthesis of green nanoparticles from citrus peels. Thirdly, the study elaborates upon the applications of citrus peels in developing various functional foods along with their quality attributes. However, the review is not devoid of certain limitations. For instance, the use of citrus fruit peels in different animal feeds has been left out. Although, the role of different citrus peel derived biomolecules in improving human health has been mentioned in Table 1, but the same has not been discussed in details.

The studies discussed touch upon the cost effectiveness of the processes involved but lacks in explaining the detailed cost analysis for assessing the real world market potential of citrus peels.

**Table 8**

Edible films and coatings made from citrus peels and their uses.

Fruit scientific name	Common name	Matrix	Food applications	Beneficial effects	Reference
<i>Citrus aurantium</i>	Bitter orange	Zein powder, glycerol	Rainbow trout	The sensory analysis primarily favored the samples with coating, enhanced with different quantities of extracts all through the sensorial assessment; in addition, the application of multiple coating layers also extended the fish shelf life by 12 days	[189]
<i>Citrus limetta</i>	Sweet lime	Glycerol, soya lecithin	<i>Pangasius pangasius</i>	Samples wrapped in active films exhibited a low surface microbial count of $3.28 \pm 0.16$ log cfu/cm <sup>2</sup> as compared to the samples wrapped in polyethylene; the hardness values went up throughout the storage period, while the springiness and cohesiveness of all the wrapped samples started to decline from day 0–12	[190]
<i>Citrus sinensis</i>	Orange	Gelatin, glycerol, D-sorbitol	Shrimp	The microbiological and sensory examination results indicated that refrigerated shrimps having gelatin film coating and containing orange peel derived essential oil possessed a 15-day shelf life, whereas the shelf life of control group was 7 days	[191]
<i>Citrus sinensis</i>	Orange	Glycerin, 0.2% Tween 20	Rainbow trout fillets	The findings showcased that all treatment groups experienced a significant increment in the counts of total aerobic psychrophilic, coliforms, lactic acid, and mesophilic bacteria, along with pH, peroxide value, thiobarbituric acid, and total volatile base nitrogen during storage; treatments with salep coating containing orange peel derived essential oil displayed a significantly lower enhancement in these parameters ( $p < .01$ )	[192]
<i>Citrus lemon</i>	Lemon	Gelatin	Cheese	Enhanced cheese longevity by inhibiting yeast molds and aerobic mesophilic bacteria proliferation, responsible for deterioration	[193]
<i>Citrus lemon</i>	Lemon	Starch, glycerol, sodium alginate	Tofu, and strawberry	The use essential oil from lemon peel at 0.6% and 1% concentration into edible coatings resulted in a substantial reduction in the fresh strawberry and tofu deterioration	[194]
<i>Citrus sinensis</i>	Orange	Pectin	Table grape	The assessment of Red Globe grapes for edible coating showed advantageous impacts mainly on the improvement of color and reduction of weight, while not influencing the sensory attributes; also, the coating were effective in preserving the grapes for 35 days at 4 °C temperature	[195]
<i>Citrus sinensis</i>	Orange	Gelatin	Cheese	During storage in refrigerator, the wrapping improved the textural and physicochemical characteristics of cheese, along with its microbiological stability	[196]

## 12. Conclusion and future prospects

Citrus peel-derived biomolecules play a crucial role in the production of green nanoparticles, carbon dots, bio-adsorbents, and biochar. Citrus peels act as catalysts that enhance the transesterification/esterification rate in the production of biodiesel. Phytochemicals from citrus peels influence the quality of EOs, aroma, flavor, and the overall acceptability of functional foods. Progressive advancements in extraction methods, 3D printing, and bioinformatics have led to new avenues focusing on improving the yield and efficacy of citrus peel-derived products. Besides, extensive research is required to establish the innovative cost-effective integrated bio-refinery approach employed for the absolute valorisation of citrus wastes at an industrial scale, capable of opening new opportunities to develop more bio-based products followed by the efficient exploitation of resources.

### CRedit authorship contribution statement

**Harsh Kumar:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Shivani Guleria:** Writing – review & editing, Visualization. **Neetika Kimta:** Writing – review & editing, Formal analysis, Data curation. **Eugenie Nepovimova:** Writing – review & editing, Validation, Supervision, Project administration. **Daljeet Singh Dhanjal:** Writing – review & editing, Formal analysis. **Nidhi Sethi:** Writing – review & editing, Validation. **Tejas Suthar:** Writing – review & editing, Validation. **Ayaz Mukarram Shaikh:** Writing – review & editing, Visualization, Validation, Resources, Investigation, Formal analysis, Data curation. **Kovács Bela:** Writing – review & editing, Validation, Supervision, Resources, Project administration. **Endre Harsányi:** Writing – review & editing, Visualization, Resources, Project administration, Funding acquisition.

### Ethics approval statement

Not Applicable.

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Not Applicable.

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### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Data availability

Data will be made available on request.

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