Industrial reuse of orange peel: A review of current applications

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ABSTRACT
Citrus fruits are valued globally for their high nutritional value. However, industrial processing, especially juice extraction, generates by-products that are often discarded or used in animal feed. Orange peel, a byproduct of this process, is a rich source of essential components that can be transformed into high-value bioproducts. Managing these wastes is challenging due to their high quantity, physicochemical properties, and seasonality of production. This study aims to explore the sustainable use of orange peel waste to generate new bioproducts. A literature review was conducted on the use of new technologies in orange peel waste. This encompasses several potential applications for the peel, including packaging production; use in bakery products; extraction of biologically active compounds for pharmaceutical or cosmetic use; extraction of pectin, used as an emulsifying, stabilizing, gelling and thickening agent; use in the biorefinery for the production of biodiesel, bioethanol and biogas; in the treatment of water and effluents; and in obtaining new chemical products, such as solvents. Finally, orange peel waste is a potential source for obtaining high value-added materials in various industries, contributing to a circular economy and reducing environmental liabilities.

Keywords: Citrus waste, Bioproducts, Innovation, High added value.

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INTRODUCTION

Worldwide, the citrus industry is recognized as an important commercial base between citrus exporting and importing nations. Countries such as South Africa, Brazil, China, the United States of America, and Mexico are exporters involved in large trades (Gupta *et al*., 2023).

Oranges, consumed worldwide, are extremely valued due to their pleasant taste and their nutritionally beneficial composition for health. Among its notable components are phenolic compounds, folate, heteropolysaccharides, and vitamin C (Pan *et al*., 2023).

Citrus fruits constitute about 18% of global fruit production, and oranges, as the most cultivated in the world, account for 60% of this citrus production. Brazil, China, India, and the United States stand out as major producers, also being significant consumers due to the abundance of these fruits in their territories. Of the producing countries, more than half of the global production of orange juice is controlled by Brazil, which exports 98% of this volume in its concentrated form (Allegri *et al*., 2024; Gupta *et al*., 2023; Ferreira *et al*., 2020).

The continuous agricultural activities to supply basic foods to the growing population, together with the intense growth of industrial activities, have led to an increase in the generation of solid waste, whose inadequate disposal contributes to environmental pollution. Although they are often reused as animal feed, many are still thrown away, especially by small producers, who lack adequate means for correct disposal. This disposal, most of the time, involves burning or abandoning the material in open landfills, which results in dangerous consequences, such as high energy demand, production of leachate (groundwater pollutants), greenhouse gas emissions, and negative impacts on human health (Kariim *et al*., 2024; Sanchez *et al*., 2023).

Scientists are increasingly interested in investigating agricultural and industrial leftovers, as they are rich in antioxidants and dietary fiber, as well as contributing to the reduction of pollution. In particular, the disposal of citrus peels is a major waste of resources, as studies indicate that these by-products contain the highest concentrations of bioactive components of fruits (Ritika *et al*., 2024; Wang *et al*., 2023).

Due to the fact that 50-60% of the orange juice produced succeeds in solid waste, it is essential to convert them into economical products to mitigate indiscriminate burning and use them as raw material for new industries. Thus, orange peels have received a lot of attention to evaluate their potential uses (Fehlberg *et al.*, 2023; Kariim *et al*., 2024).

The orange has a varied size and a rounded-oblong shape. Its bark is composed of two parts, the flavedo, which is the colored outer layer containing oily sacs, and the albedo, the white inner part rich in pectin. The pulp is divided into segments that may contain seeds. Peels, which are rich in sugars and monoterpenes (mainly D-limonene), and seeds, composed of nitrogen-free extract, lipids, crude proteins, and fiber, are important by-products (Dongre *et al*., 2023).

In recent years, there has been a significant increase in research focused on the extraction of compounds of high biological value using various traditional and ecological technologies, in addition to their applications in different industries (Panwar *et al*., 2021). Therefore, this review article seeks to offer an overview of the various potential applications of orange peel, from its simplest uses to innovative methods for the use of this waste, including concepts of circular economy and upcycling.

METHODOLOGY

A literature review was conducted on the use of new technologies in orange peel waste waste. The search engine Science Direct was used, in which the keywords "orange juice", "waste recovery", "residue", "orange by-products", "orange peel", "value-added", "pharmacological", "limonene", "carotenoids", "phenolic compounds", "biofuel" and "wastewater treatment" were applied in different combinations with the Boolean operator "AND". The search was restricted to articles published in the last 5 years, including both review and research studies. Additional sources were incorporated through the snowballing technique, which involves the addition of references cited in the reviewed articles. In total, 41 sources were identified for detailed analysis.

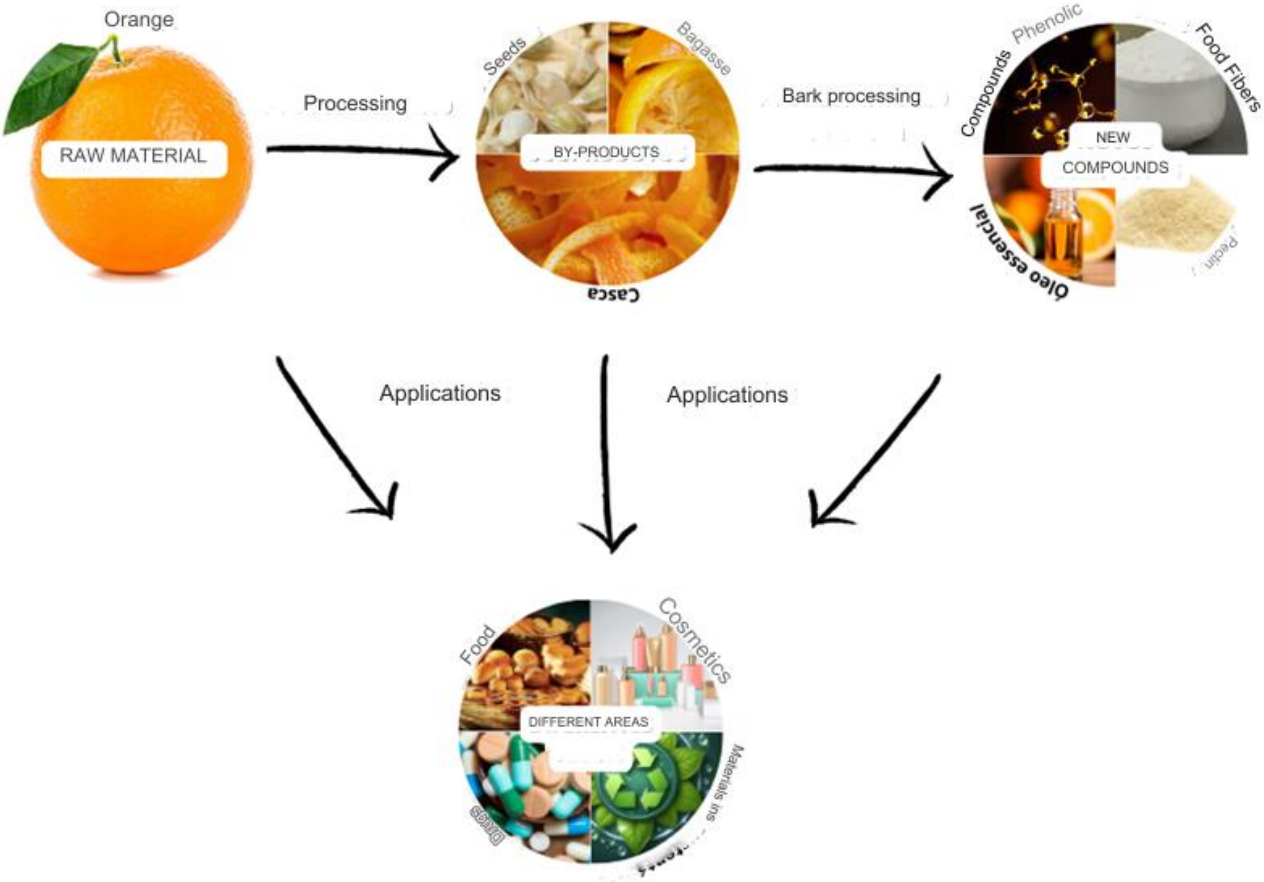
DESTINATION OF WASTE

Terrestrial and water pollution resulting from the generation of agricultural waste have become a worldwide concern. The search for intelligent solutions to manage and eliminate these products has been the subject of much research. Orange peel waste has aroused considerable interest due to the extensive global production of oranges, of which a significant portion is transformed into juice, which ends up producing a large volume of waste (Fehlberg *et al.*, 2023).

One of the essential pillars for the conservation of natural resources is the Circular Economy (CE). EC promotes sustainability by focusing on eliminating waste and continuously reusing materials. This approach integrates by-products and waste back into the production chain, reducing waste production and reducing environmental impact. Upcycling, a key component of this approach, involves turning waste materials into new, higher-value products. Therefore, to reduce the environmental impact of food waste management, such as orange waste, and promote an approach based on the circular economy, treatments that aim to reuse by-products in the generation of new value-added products must be implemented (Capelleveen *et al*., 2023; Atinafu *et al*., 2024; Fraia *et al*., 2024).

The citrus fruit processing sector is generally segmented into four main stages: transportation of the harvested fruits to the processing plant; washing, sorting, and grading; extraction of the juice with subsequent heat treatment; and final packaging. After obtaining the juice, a significant amount of solid and liquid waste is generated, including peels, seeds, bagasse, and wastewater. These residues, especially the bark, can be reused as a potential substrate to obtain various high value-added products (Figure 1) (Panwar *et al*., 2021).

Figure 1 – Applications of orange waste, especially peel, in different areas.



Source: Author (2024)

Orange peel waste has a diverse composition, including approximately 75-85% water, 6-8% mono- and disaccharides, such as sucrose, glucose, and fructose, 1.5-3% polysaccharides, such as pectin, cellulose, and hemicellulose, and 0.5-1.5% organic acids, such as citric acid and malic acid. In addition, they are rich in important antioxidants such as polyphenols and carotenoids, and contain significant amounts of trace elements such as zinc and magnesium. With a pH generally between 3 and 5, and a marked presence of essential oils, mainly limonene, these residues offer a wide range of applications after extraction by different methods (Bouaita *et al*., 2022; Pagliarini *et al*., 2024; Krivošija *et al*., 2023).

ORANGE PEEL IN THE PRODUCTION OF BIOFILMS

Orange peel waste is usually converted into citrus pulp pellets for livestock feed or disposed of in landfills. Innovative ways of using this waste have led to the exploration of its integration into plastics to add value to waste, while reducing the source of plastic and improving its properties (Fehlberg *et al*., 2023).

McKay *et al*. (2021) and Fehlberg *et al*. (2023), reported the use of orange peel powder for the production of films for food packaging. The peels, after being collected, were freeze-dried, ground in a hammer mill, sifted and incorporated into the production of a film.

McKay *et al*. (2021) produced, from sweet orange peel powder (*Citrus sinensis* var. Valencia), a linear low-density polyethylene plastic film, insulated, and combined with the orange peel powder through the thermohydraulic press. The same type of orange and polyethylene were used by Fehlberg *et al*. (2023) for the production of plastics combined with powder in different concentrations. The process used by them was the extrusion of blown film.

McKay *et al*. (2021) evaluated the antimicrobial efficacy of plastic obtained from orange peel residues against fungi often found in food. Orange peel powder, alone, showed good results in inhibiting the growth of *Botrytis cinerea*, *Aspergillus niger* and *Penicillium* sp. However, when incorporated into the film, the antimicrobial activity was maintained only against *B. cinerea*, although with lower efficacy when compared to the isolated powder. This decrease in efficacy is attributed to the partial loss of antimicrobial compounds, such as limonene and citral, during film processing.

Additionally, Fehlberg *et al*. (2023) conducted an analysis addressing the morphology of the blown film biocomposite, along with its mechanical, barrier, optical, and thermal properties, in order to determine the maximum amount of orange peel powder that could be incorporated into the plastic. The results indicated that it is feasible to incorporate up to 11.5% orange peel powder in the composition of the plastic. Thus, the reincorporation of orange peel as a raw material in the packaging production process also offers a valuable opportunity to promote the circular economy.

ORANGE PEEL IN BAKING

In food products, residues can add significant nutritional properties. Orange peel has a high content of bioactive compounds and dietary fibers that offer several health benefits. By including orange peel powder in baked goods, manufacturers can develop more nutritious foods, improve their health-promoting properties (Talens *et al*., 2022), and at the same time decrease waste (Gasparre *et al.,* 2024).

According to Cirrincione *et al*. (2024), orange peels are used to produce flours, encapsulated essential oil, encapsulated extract, and fibers. Orange peel flours are used in the production of bread, cookies and cakes; encapsulated essential oil is used in cakes; the encapsulated extracts are applied to brownies; and the fibers are incorporated into muffins.

Gasparre *et al.* (2024) studied the use of orange peel by-products in the baking of gluten-free flatbreads. The replacement of traditional flours with orange peel powder resulted in doughs rich in fats, minerals and fiber, with an intense yellow color and good water retention. As a result, the waste has shown great potential as a nutritional and technological improver, promoting sustainability and offering an economical alternative to gluten-free breads. However, sensory analyses were not performed to assess consumer acceptance.

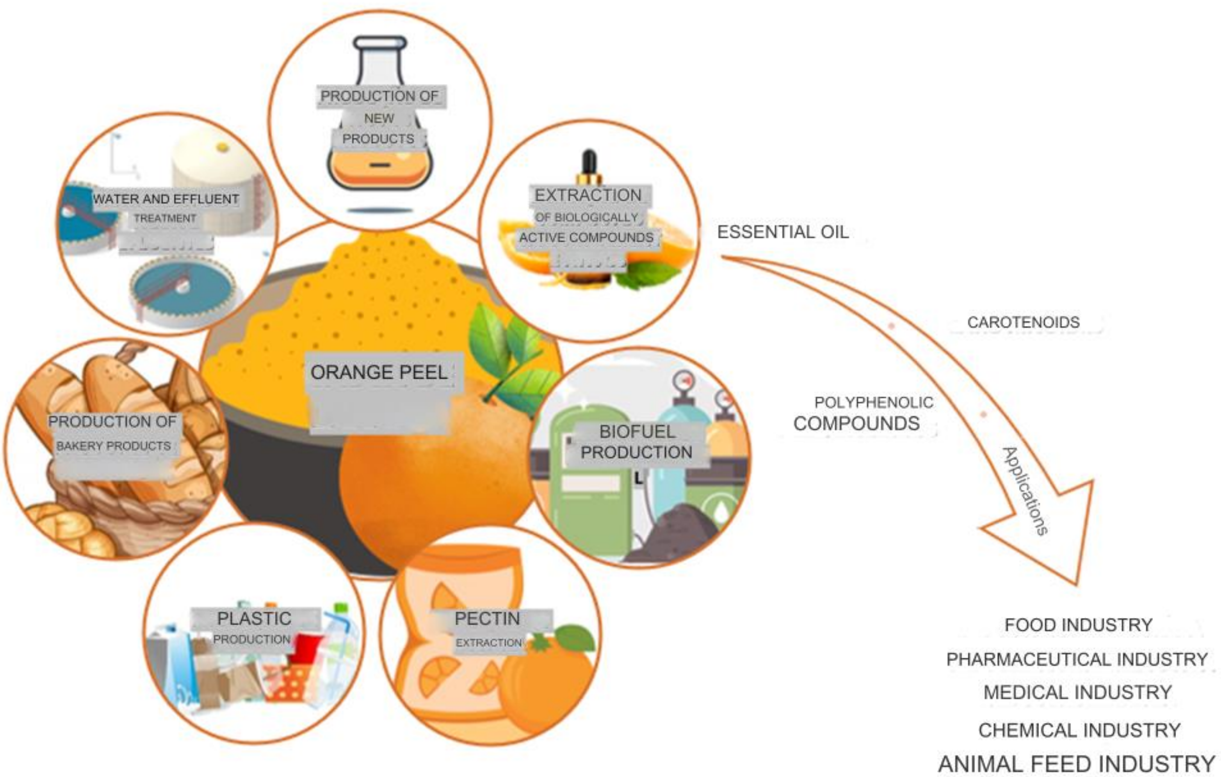
Although orange by-products improve the nutritional quality of baked goods by providing fiber, antioxidants, polyphenols, and essential oils, sensory attributes can be adversely affected. Cirrincione *et al*. (2024) point out that the addition of these by-products in larger quantities can alter the sensory characteristics of the food, resulting in less acceptance by consumers.

ORANGE PEEL IN OBTAINING BIOLOGICALLY ACTIVE COMPOUNDS

Industrially, the bioactive compounds present in orange powder extracts are widely studied and used.

Polyphenolic compounds, carotenoids, and essential oil of orange peel are the constituents that stand out for their beneficial effects on health (Figure 2). The aroma of orange peel essential oil is a result of some of its components, alcohols, aldehydes, esters, ketones and terpene hydrocarbons. Limonene, a terpenoid, is identified as the main component of the oil, however, other compounds, such as citronellal, geranial, linalool, octanal, and α-terpineol, are also present, albeit in lower concentrations (Krivošija *et al*., 2023).

Figure 2 – Possibilities of products obtained from orange peel with a focus on biologically active compounds.



Source: Author (2024)

Several terpenoids, such as limonene, are volatile at room temperature and contribute to the characteristic aroma of plants and fruits (Ritika *et al*., 2024). On the other hand, phenolic compounds are mostly responsible for the antioxidant activity of the fruit (Wang *et al*., 2023). The extraction of these compounds from the fruit peel for incorporation into pharmaceuticals must be strictly controlled to ensure the stability of the bioactive components.

Several techniques have been employed to extract phenolic compounds from citrus fruit peels. These include conventional solvent extraction, enzyme-assisted extraction, accelerated solvent extraction, microwave-assisted extraction, supercritical water extraction, supercritical fluid extraction, and ultrasound-assisted extraction (Wang *et al*., 2023). To obtain the essential oil, the methods include mechanical extraction through cold pressing, thermal methods with water or steam, such as steam distillation, microwave-assisted thermal extraction, ultrasonic extraction, extraction with supercritical CO2, and biosolvents (Teigiserova *et al*., 2021) (Table 1). However, it is crucial to note that while all of these methods enable product recovery, they can also lead to degradation of bioactive components due to heat, long extraction times, limitations in mass transfer, resistance, enzymatic denaturation, and high technical and cost requirements (Wang *et al*., 2023).

Table 1 – Main methods used to obtain biologically active compounds from orange peel.

Methods	Compounds			References
	Polyphenols	Carotenoids	Essential oil	
Ultrasound-assisted extraction	X	X	X	Wang *et al*. (2023) Teigiserova *et al*. (2021) Murador *et al*. (2019) Krivošija *et al*. (2023)
Extraction with supercritical carbon dioxide at high pressure	X	X	X	Krivošija *et al*. (2023) Teigiserova *et al*. (2021) Murador *et al*. (2019)
Enzyme-assisted extraction	X			Wang *et al*. (2023)
Conventional solvent or biosolvent extraction	X	X	X	Wang *et al*. (2023) Gómez-Mejía *et al*. (2019) Murador *et al*. (2019) Myrtsi *et al*. (2022) Teigiserova *et al*. (2021)
Microwave-assisted extraction			X	Teigiserova *et al*. (2021)
Mechanical extraction - cold pressing			X	Teigiserova *et al*. (2021)
Ionic liquid extraction		X		Murador *et al*. (2019)
Thermal extraction with water or steam		X	X	Teigiserova *et al*. (2021) Myrtsi *et al*. (2022)

Source: Author (2024)

Terpenoids are widely used in ethnomedicinal and herbal practices due to their aromatic properties. In addition, they have antibacterial activity against certain foodborne bacteria, such as *Escherichia coli*, *Staphylococcus aureus*, and *Salmonella typhimurium*, revealing great anti-biofilm potential (Ritika *et al*., 2024). Limonene, for example, can be used in a variety of applications in the food, pharmaceutical, and medical industries, serving as a green solvent, natural insecticide, and chemopreventive agent with anticancer properties (Teigiserova *et al*., 2021).

Biologically active polyphenols, such as phenolic acids and flavonoids, demonstrate antioxidant, anti-inflammatory, antiproliferative, antiallergic, antiviral, anticarcinogenic, neuroprotective, and antimicrobial properties. Therefore, citrus peel residues generated by the juice industry can be used in dietary supplements, as raw materials in cosmetics, and as natural additives in food and pharmaceutical products (Gómez-Mejía *et al*., 2019).

Orange peel, in turn, can also be a valuable source of carotenoids, natural pigments that give color to fruits. Carotenoid consumption is associated with improvements in the immune system and a reduced risk of developing degenerative diseases such as cancer, cardiovascular disease, Alzheimer's, and macular degeneration (Murador *et al*., 2019). These can be incorporated into the food industry as natural colorants and nutritional food fortifiers; in the cosmetics industry, in skin care products and make-up due to their antioxidant properties; in the pharmaceutical industry in medicines, supplements and nutraceuticals; and in the animal feed industry. Extraction methods, such as microwave-assisted extraction, enzyme extraction, supercritical fluid extraction, ultrasound-assisted extraction, and pulsed electric field-assisted extraction, i.e., green extraction technologies, can be utilized to achieve high carotenoid recovery rates (Myrtsi *et al*., 2022; Silva *et al*., 2024; Gebregziabher *et al*., 2023). It is observed, therefore, that orange peel is a rich source of bioactive compounds, with the potential to be used in the manufacture of various biochemical products.

ORANGE PEEL IN OBTAINING PECTIN

Pectin, a complex carbohydrate, is widely used by the food industry in a variety of applications. It performs essential functions as a gelling agent, emulsifier, stabilizer, and thickener. In the bakery industry, pectin is employed to improve the texture of products, while in confectionery, it is essential in the preparation of fillings and fruit-based products such as jams. In beverages, pectin is able to stabilize and improve the texture of fruit juices and other fruit-based beverages. In addition, pectin is also used in the manufacture of packaging, evidencing its versatility and importance in the food sector (Silva *et al*., 2024; Castro *et al*., 2024).

About 85% of commercial pectin is extracted from the residues of citrus peels, such as lemon, grapefruit, and orange. These peels contain between 1.5% and 18% pectin, depending on whether they are fresh or dried (Suri *et al*., 2022). Pectin not only has valuable technological properties, but also biological benefits. This acts as an essential dietary fiber that promotes the individual's gastrointestinal health. Such action reduces cholesterol and protects the body against different diseases, such as diabetes and cancer (Silva *et al*., 2024).

Orange peel is a particularly rich source of pectin, accounting for about 28% of its dry weight. Extraction methods such as acid extraction, enzymatic hydrolysis, microwave-assisted extraction, and ultrasound are used to obtain pectin from orange peel (Silva *et al*., 2024).

Agricultural by-products are rich in bioactive compounds, but these compounds are unstable under environmental and industrial conditions. Microencapsulation is a technology that can protect these compounds, forming capsules of micrometric to millimeter size. Different encapsulating materials, such as polysaccharides, lipids, and proteins, have been used (Comunian *et al*., 2021). Kaderides *et al*. (2019) used orange residue powder to encapsulate pomegranate peel extract, obtaining high efficiency (99.77%) and a yield of 12.99%, lower than when compared to traditional materials.

Pectin, extracted from orange peel, can also be used as a gelling agent, meeting the demand for natural ingredients in the food industry. Li *et al*. (2024) showed that orange peel suspensions, ground for more than 60 minutes in a stirred mill, form hydrogels. This suggests that milling may improve the utilization of orange peel as a functional ingredient due to the high-methoxyl pectin.

Another application of pectin extraction is described in the work of Manthei *et al*. (2024), in which, from orange peel and apple pomace, they extracted by high-pressure homogenization and enzymatic hydrolysis, large quantities of oligosaccharides with potential uses as a prebiotic.

ORANGE PEEL IN OBTAINING BIOFUELS

Fossil fuels, such as coal, oil, and methane, are the world's main sources of energy, but their non-renewable nature leads to scarcity and contributes to global warming. The increasing demand for energy due to industrialization and population growth, highlights the urgent need for renewable and sustainable sources. The production of biofuels from biomass is a promising solution, as it offers an efficient and ecological alternative that can reduce dependence on fossil fuels and consequently protect the environment (Kariim *et al*., 2024; Viswanathan *et al*., 2022).

Orange peel is high in carbon and contains large amounts of complex sugars such as cellulose, lignin, and hemicellulose. These components can be converted into soluble sugars through the use of enzymes or hydrolysis techniques with dilute acid. Thus, a viable option to value this waste is to produce biofuels, such as biodiesel, bioethanol and biogas (Kariim *et al.*, 2024).

According to Mawlid *et al*. (2024), orange peel powder was used to produce hydrochar (carbonaceous material) through hydrothermal carbonization. This activated hydrocarbon was then functionalized with potassium carbonate (K2CO3) to generate a heterogeneous catalyst. The catalyst was used in the transesterification reaction of a residual frying oil, which resulted in the production of biodiesel. The process demonstrated the effectiveness of functionalized orange peel hydrochar as a catalyst in the conversion of waste oils into biofuel, highlighting a sustainable and innovative approach to the use of plant waste.

On the other hand, Viswanathan *et al*. (2022) used orange peels as a raw material for the manufacture of biofuel. Bitter orange oil, obtained through steam distillation, was the main source used in the production of biodiesel. The results of the study demonstrated that this biofuel can be a renewable low-viscosity option, suitable for engines, providing low emissions and contributing to a more sustainable and cleaner environment.

In addition, fruit and vegetable residues, as well as other raw materials rich in natural sugars and cellulosic biomass, are also used for the production of bioethanol. The process of producing bioethanol from agro-waste involves steps such as pre-treatment, enzymatic hydrolysis, fermentation and distillation. Mishra *et al*. (2022) demonstrated that orange, banana and pineapple peel residues can be fermented with immobilized microorganisms under various conditions, which leads to efficient bioethanol production.

Orange peel waste can also be used in the production of biogas (Sanchez *et al*., 2023). Although the D-limonene present in the essential oil of the peels acts as an inhibitor in anaerobic digestion, Bouaita *et al*. (2022) demonstrated that, under controlled conditions, the anaerobic digestion of orange peel waste is efficient in generating biogas. Even with the high content of limonene, an antimicrobial agent, the researchers found that by maintaining a low concentration of this substance in the anaerobic digester, inhibition of the process can be avoided. To achieve this goal, they performed anaerobic co-digestion of the orange peels with the organic fraction of municipal solid waste, which helped dilute the D-limonene in the organic mixture (Bouaita *et al*., 2022). Therefore, orange peel is a promising waste for the generation of renewable energy sources.

ORANGE PEEL IN WATER AND WASTEWATER TREATMENT

Adsorption is widely used to remove drugs, dyes, and heavy metals from wastewater. This process is fast, economical, simple and highly effective. Currently, researchers are focused on the development of bioadsorbents made from waste for the treatment of water and effluents. The choice for bioadsorbents is justified by their low production cost, availability, ease of handling, possibility of regeneration, and respect for the environment (Khalfaoui *et al*., 2024).

Gao *et al*. (2024) developed an adsorbent aerogel from orange peel waste combined with amino MXene, a two-dimensional inorganic compound, with the aim of removing heavy metals from effluents. The results indicated that this material had excellent adsorption properties for pentavalent vanadium in water, reaching a maximum adsorption capacity of 748.42 mg/g at a pH of 4.

Khalfaoui *et al.* (2024) synthesized two bioadsorbents from artichoke leaves and orange peel residues treated with zinc chloride (ZnCl2). These materials were evaluated under different operating conditions for the adsorption of ketoprofen, a non-steroidal anti-inflammatory drug, in water. The results showed that the adsorption capacity of the orange peel and artichoke leaf bioadsorbents reached 96% and 90%, respectively, with adsorption capacities of 1,937 mg/g and 1,803 mg/g. Thus, these bioadsorbents have been shown to be effective for the treatment and removal of medications, such as ketoprofen, from wastewater.

Roy et al. (2024) described another efficient application of waste. They developed an interfacial solar steam generator using charred orange peel to desalinate ocean water and produce fresh water. The resulting three-dimensional photothermal material demonstrated an evaporation rate of 1.86 kg m^{-2} h^{-1} and an energy efficiency of 87.90% under a solar irradiation of 1 kW/m^2. In addition, the system achieved a salt rejection rate of 99.99% during desalination and a complete removal of dyes during water purification. This solar evaporator has proven to be an efficient and low-cost solution for interfacial solar vapor generation, highlighting the potential of biological waste as effective photothermal materials.

ORANGE PEEL IN THE MANUFACTURE OF NEW CHEMICALS

Orange peel waste, important by-products of biomass resulting from juice manufacturing, can be harnessed as a valuable resource for the production of a variety of chemicals (Allegri *et al*., 2024).

Allegri *et al*. (2024) presented a catalytic process that involved the dehydrogenation of limonene to p-cymene and subsequent hydrogenation by catalytic transfer of methyl levulinate to γ-valerolactone. This solvent, which is non-toxic and bio-based, has gained attention as an important precursor in industrial chemistry.

In addition, Qamar *et al*. (2023) reviewed the use of cost-effective materials, such as industrial and household waste, in the production of biosurfactants, highlighting their ability to replace expensive synthetic materials. Food waste and agro-industrial by-products, such as sugarcane bagasse, cassava wastewater, rice straw, banana stalks, corn cobs, and fruit peels, were investigated as efficient substrates. Orange peel, used as a substrate for *Bacillus licheniformis*, has shown potential in the production of lipopeptides applicable in the biodegradation of hydrocarbons.

Another application of the residue was described by Ousaadi *et al*. (2021), in which they demonstrated that orange peel can be used in the production of α-amylase by *Streptomyces* sp. Microbial enzymes, which are widely used in various industries such as textiles, bakery, alcohol manufacturing, and detergents, are expensive when produced with synthetic media. In the study, the researchers demonstrated that orange peel, an economical and available agricultural waste, can replace these expensive means. The research optimized the cultivation conditions of *Streptomyces* sp., using orange peel as the only source of carbon in low-cost media, confirming the viability of agricultural residues as growth substrates.

CONCLUSION

This updated review explores the growing interest in the use of orange peel by-products, mainly from the juice industry, and highlights the variety of value-added products that can be derived from these wastes. The industrial application of orange peel is promising in several areas due to its abundance and the richness of valuable components, such as fermentable sugars and bioactive compounds.

Orange peel has been extensively studied and used in the production of a wide range of bioproducts in the food and biotechnology industries. Through different methodologies, it is possible to transform this waste into valuable products, including essential oils, pectin, biofuels, chemicals, adsorbent materials, biologically active compounds, bakery products, and plastics.

These products not only represent a sustainable and cost-effective approach to waste management, but also offer environmental and economic benefits to the establishments that adopt them. In addition, the use of orange peel waste helps to mitigate the negative environmental impacts associated with improper waste disposal, promoting sustainability and the circular economy.

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