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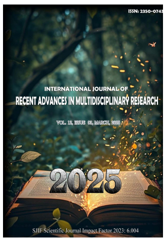

REVEIW ARTICLE

INDUSTRIAL APPLICATION OF DIFFERENT PARTS OF CITRUS PLANTS IN BIOTECHNOLOGY SECTORS

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ABSTRACT

Citrus sinensis (sweet orange) and Citrus reticulata fruit is widely consumed the world over for its sweet juice. The peels, pulps and seeds may have some nutrients and antimicrobial properties but are essentially discarded with attendant waste generation. In this study, antimicrobial properties have been analysed in peels, pulp and seeds of Citrus sinensis (sweet orange) and Citrus reticulata (kinnow). Phytochemical screening showed the presence of flavonoid, saponin, terpenoids, proteins, carbohydrates and phenolic compounds. Flavonoid was extracted from these extracts and its quantity was analyzed using aluminium chloride assay methodology. They will be further characterized using thin layer chromatography. These extracts showed effective zone of inhibition against growth of pathogens like *Klebsiella pneumoniae and Enterococcus bacteria*. These flavonoids could be used for synthesis of nanoparticles and used commercially in biotechnology sectors.

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INTRODUCTION

Worldwide Citrus stands among the top important agricultural fruit products. Citrus fruits historically stemmed from the Southeast Asian territory. Multimedia sources indicate that tropical and subtropical areas produce over 100 million tons of citrus fruits annually in addition to numerous other growing regions. Citrus fruits make up one of the fruit groups within the Rutaceae family which includes orange and tangerines and lemon and mandarin and the pomelo family and the grape fruit genus. Each C. fruit variety exhibits distinctive characteristics through its juice content together with specific taste and flavor profile. The main citrus fruit production countries include Brazil as well as China alongside India among others. Punjab and Maharashtra together with Meghalaya and Rajasthan and Madhya Pradesh and Tamil Nadu and Assam comprise the main Indian states devoted to massive citrus fruit cultivation according to Singla (2019). The Citrus genus includes various essential fruits like oranges (Citrus sinensis) together with mandarins (Citrus reticulata) among others. Phytochemistry depends on numerous plant groups although citrus plantations remain the most valuable choice for industrial and commercial agriculture worldwide (Mohammed, 2024). The first citrus fruits developed their origins inside Southeast Asian territory.

Producers throughout tropical and subtropical climates produce over 100 million tons of citrus fruits which are farmed widely in numerous areas including multiple locations. The Rutaceae family houses citrus fruits which extend from the variety of species and hybrids between orange to tangerines to lemon to mandarin to pomelos to grape fruits. Internally different kinds of C. fruits maintain distinct juice, flavor, and taste compositions. C. fruit cultivation occurs throughout various regions across the world including Brazil and China and India among other producing nations. The cultivation of citrus fruits at large scale continues in the seven major states of India including Punjab, Maharashtra, Meghalaya, Rajasthan, Madhya Pradesh, Tamil Nadu, and Assam as reported by Singla (2019). Three vital fruit species belong to Citrus genus along with oranges (Citrus sinensis) and mandarins (Citrus reticulata). The global significance of citrus plantations as prime assets for industrial and commercial farming exceeds the importance of various plant groups to phytochemistry although their antimicrobial properties suppress microbial growth between fungi viruses and bacteria. Bioactive substances contain specific chemical qualities that disrupt essential microbial functions and dissolve cell membranes thus blocking enzymes which are essential to microbial survival. Terpenes show a broad range of antimicrobial properties so doctors consider them important agents for combating pathogens that resist current medications for microbes. Scientists have proven that terpenes show antimicrobial effects against a wide range of pathogens thus making them promising agents against drug-resistant germs. The manufacturing of orange juice mainly takes place within two specific territories: Sao Paulo in Brazil and Florida situated in United States of America. Brazil remains the leading exporter of orange juice at present. The commercial world produces citrus as one of the top significant commercial fruit crops globally. This article examines the chemical nature alongside the geographical origin and classification system of multiple citrus flavonoid groups. This paper outlines information from scholarly works and displays the flavonoid contents in particular citrus strains alongside their antimicrobial properties and health advantages(Addi, 2021).

REVIEW OF LITERATURE

About citrus fruit: Historical background: The citrus did not exist in America until the transportation of its first specimens by Christopher Columbus during his 1493 voyage although Brazil together with the United States presently lead as major commercial citrus producers worldwide. All indications reveal the origin of citrus trees exists somewhere within the Eurasian geographical region. The first citrus plant recognized by Europeans was likely citron (Citrus medica). The presence of citron in ancient Egypt stems from its depiction on walls at the Karnak Temple which dates from 3000 years ago. The Jews possibly learned about citrus trees at the sixth century BC based on their departure from Sinai mentioned in Leviticus through the term "fruit of the beautiful ('hadar') tree" but the Bible itself did not directly reveal citrus trees. During the late fourth century BC Alexander the Great with his armies introduced citron from the east likely India to European nations according to Theophrastus who lived in Greece at the same time. He established that the east (Median and Persia) was already cultivating citron. The Western Mediterranean region received citron from Persian territory during early Roman times with lemon appearing as the second early citrus fruit and Sour orange (C. aurantium), lime (C. aurantifolia), pummelo (C. maxima) arriving in the 10th century AD(Langgut, 2017). The introduction of mandarin (C. reticulata) to the world occurred early in the nineteenth century after sweet orange (C. sinensis) became available in the late fifteenth century. The western import of potatoes relied on trade routes which spread southward from China before reaching northern Africa and the Iberian Peninsula as apparent relay stations (Ramon-Laca, 2003).

People across the globe eat citrus sinensis (sweet orange) and citrus reticulate (mandarin) foods because these plants naturally protect immunity by acting as antioxidants and antimicrobials. The fruits of mandarins (C. reticulata) differ considerably in their size along with their shape and color characteristics while also featuring simple peeling abilities. Different taxonomists have formally identified multiple wild species related to mandarins. C. indica exists among mandarin types but Tanaka mistakenly identified it as a basic mandarin while the variety in fact derives from citron origins or represents a citron hybrid. Most wild mandarin species exist in South China territory with C. tachibana being the native mandarin of Taiwan and Japan. The Kinnow serves as a widely cultivated mandarin hybrid which yields abundantly throughout the wider Punjab region of Pakistan and India. Moreover, various wild mandarins were discovered across Hunan and Jiangxi and Guangxi provinces during the past four decades. Commercial farming professionals introduced the kinnow citrus hybrid to the market in 1935 as a new agricultural product. The worldwide cultivation of Sweet Orange continues to increase because people prize its nutritional value combined with essential vitamins and phytochemical compounds and this important economic species exceeds other citrus plantings in global production. The sweet orange floral origin sequence had 121 randomly chosen uni-genes and loci, which provided a statistically verified genome-wide coverage (Zhong, 2013; Wu, 2016). Every analyzed sweet orange locus demonstrated parental material from mandarin because at least one allele originated from the mandarin parent.

Botany: Sweet orange stands apart from sour orange and C. aurantium and C. reticulata and Mandarin orange as a small evergreen tree measuring 7.5 meters high and reaching as high as 15 meters. The world considers this fruit tree as one of its most frequently cultivated kinds since ancient Chinese farmers first started cultivating it in their homeland. Commercial farmers grow sweet orange trees throughout tropical and semi-tropical regions as well as certain warm temperature climates across the globe today (Nicolosi, 2000). The maturing fruit develops orange or yellow colors and takes the form of a globose to oval shape ranging from 6.5 to 9.5 cm across. The fruit exists in anatomical dissimilar sections where the endocarp functions as pulp and juice sacs but the pericarp performs as peel and skin (Fig. 1).

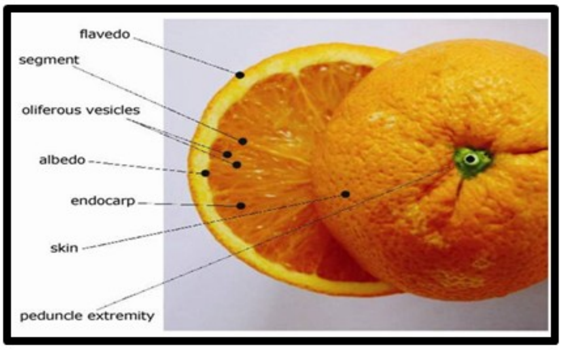

Fig. 1. Different parts of sweet orange

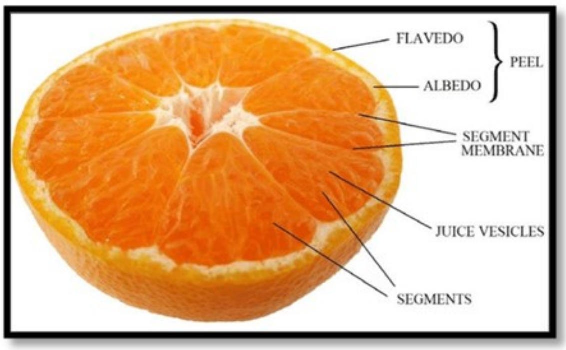

Fig. 2. Different parts of Kinnow

Epicuticular wax on the epidermis carries multiple aromatic oil glands responsible for producing the unique skin fragrance. The production amount of wax depends on plant growth rate

Table 1. Taxonomy of citrus fruit

Kingdom	Plantae
Phylum	Angiosperms
Class	Eudicots
Order	Sapindales
Family	Rutaceae
Genus	Citrus

and environmental conditions together with the specific variety type. Kinnow serves as the dominant cultivated offspring of rough lemon (Citrus jamberry) that effectively thrives in Punjab's environmental zone. Variability exists across two major areas of Kinnow mandarin (Citrus reticulata) characteristics including vegetative features and fruit features. This variability includes variations in fruit sizes and shapes, peel thickness, coloration, skin peelability, time of maturity, number of segments, central axis solidity or hollowness, sweetness, acidity, flavor, juice content, embryo numbers per seed, seed form, seed size, fruit dropping tendencies and percentage of fruit retention on the mother plant. A complete analysis evaluated the population variation of Kinnow seed embryo cells because they originate from vegetative cell lines present in fruit-bearing branches. Rough lemon rootstock functions as an indigenous and powerful dominant plant variety with natural adaptability. A budded tree obtains its support from its root system while the roots also function to take in water and nutrients and store carbohydrates in leaves and produce growth regulators and support the scion in adapting to different soil types and can provide disease resistance. When selecting rootstock seedlings it becomes essential to choose the right ones because of these fundamental reasons(Altaf, 2008).

Taxonomy of citrus fruit: The taxonomy and systematics of the genus become complicated because many identified species multiply through seeds (using apomixis) as hybrids that breed asexually. Genetic research proves some true-breeding wild species have hybrid origins which makes counting natural species challenging. Domesticated citrus species including mandarin oranges and papeda and pomelo along with citron resulted from natural or artificial hybridization of only a small number of fundamental original species. The commercial outcomes of fruits including oranges, grapefruits, lemons, limes and particular tangerines result from both natural and artificial citrus hybridization. The taxonomy of citrus fruit contains the familiar oranges together with lemons and kinnow as well as other familiar fruits according to (Klein, 2014). The research uses two citrus fruit varieties with their peelings and pulps and seeds as experimental materials. The citrus hybrid Citrus reticulata originated from the cross between two citrus cultivars King (Citrus nobilis) and Willow Leaf (Citrus deliciosa). Citrus reticulata achieves fame through its combination of bright orange hue and tasty sweet-tart flesh and juiciness (Hui Y. H., 2006).

Common name – Kinnow, Mandarin : The fruits present themselves as small round to slightly flattened objects which have thin easily removable rinds. The pleasurable texture of the pulp occupies a sweet section with no visible seeds. Origin -Southeast Asia

Appearance: The rind of Kinnow fruit has a smooth texture that features thin and peeling-friendly orange skin. The fruit grows to medium or large dimensions while bearing similarity to both mandarin and tangerine.

Flavor: People value Kinnow for their tangy flavor profile because these fruits carry an excellent union of natural sweetness with acidic notes. The juicy interior of Kinnow contains delightful citrus flavor that drives applause from fans of this fruit family.

Nutritional Value: The nutritional composition of Kinnow resembles citrus fruits since they offer vitamin C which strengthens the immune system and helps people maintain good health. Kinnows offer nutritional benefits because they combine antioxidants along with dietary fiber and contain essential mineral potassium and vital mineral calcium.

Season: Kinnow fruits exist during the winter season between December through March unless growers maintain greenhouse conditions for continuous production.

Health Benefits: Kinnow possess both vitamin C abundance along with antioxidant flavonoids which support human body defense against damaging oxidative reactions and inflammation development. Kinnow intake on a regular basis makes beneficial contributions to heart health together with digestion support and improved skin health.

Fig. 3. Kinnow

The sweet oranges identified as Citrussinensis represent a cross between Pomelo (citrus maxima) and Mandarin (citrus reticulata) which makes it the most cultivated variety of orange.

Common name – Sweet orange

Description -Round to oval fruits with thick peels
Colour -Orange, aromatic rind
The pulp is sweet and juicy
Origin -Southeast Asia

Appearance: Whole sweet oranges present themselves as round to oval structures with an orange tinge under their smooth exterior. The skin of blood oranges shows a light reddish tinge which generally appears along the fruit surface.

Flavour: Sweet oranges gain their popularity from delightful sweet pulp which also provides juiciness to the flesh. Different orange variations and levels of maturity determine how sweet or tangy the fruit taste will be.

Nutritional Value: The nutritional value of Sweet oranges stands out because they contain both vitamin C and Fiber together with different antioxidant compounds. The natural fruits also carry trace amounts of necessary vitamins A as well as folate and potassium.

Season: The time for sweet oranges is during winter in most agricultural zones yet the particular harvesting dates differ between specific orange types. The Valencia oranges grow in the fields from late spring to early summer.

Health Benefits and Nutritional Profile: Other essential nutrients besides vitamin C exist in sweet oranges which also possess vitamin A alongside potassium and calcium while offering folate as an additional benefit. The nutrition profile of these fruits benefits health through immune response improvement and vision enhancement and bone development and red blood cell development.

Fig. 4. Sweet orange

Bioactive compounds in Citrus fruits as Potential Therapeutics: By-products from Citrus fruits, including exhausted peel, seeds, pressed pulp, secondary juice (obtained by pressing the residual pulp after the primary juice extraction) and leaves, are a source of polyphenols (i.e., flavonoids and phenolic acids), sugars (i.e., glucose, fructose and sucrose), dietary fibers (i.e., pectin and cellulose), proteins, lipids (i.e., linolenic, oleic, palmitic and stearic acids), organic acids (i.e., citric, malic and oxalic acids) carotenoids (i.e., carotene and lutein), vitamins (i.e., vitamin C and vitamin B complex) and monoterpenes (i.e., limonene and linalool) (Mahato *et al*., 2018). The volume of CF peel reaches approximately 50% of the total juice extraction mass (Sharma *et al*.,2017) while containing abundant fragrant substances with dietary fibers and pectin and polyphenols and natural pigments(Rafiq *et al*., 2018). The plant oil cells inside both peel segments and cuticles store essential oils which can be obtained from citrus fruit peels. Citrus fruit tree leaves together with seeds retain tiny quantities of essential oils. The essential oil compounds of EOs come from monoterpenes and sesquiterpenes hydrocarbon series together with oxygen derivatives which include alcohols ketones aldehydes and esters. Cold-pressed citrus EOs have a long history of application in food preparation and cosmetic products and pharmaceutical applications and scientists are now studying their health advantages(Dosoky *et al*., 2018; Bruni *et al*., 2019).

The exhausted CF peel material contains pectin and dietary fibers in addition to what exists in juice along with pulp(Dimopoulou *et al*.,2019). This naturally occurring gelling agent exists in complex or insoluble forms from white to light brown color and serves as a thickener, emulsifier and stabilizer and texturizer during confectionery and jam and jelly preparations and biodegradable product development. The extraction process of Secondary CF juices produces carotenoids together with flavonoids that naturally exist within peels. Different plant foods produce carotenoids through biosynthesis methods which enable scientists to group this class into xanthophylls and carotenes depending on whether they contain oxygen or carbon atoms (Saini & Keum, 2018; Sharma *et al*., 2021) (Figure 3). Vitamin A forms from these precursors while this vitamin plays a role in tissue growth and strengthens immunity and enables optimal vision functions (Widjaja-Adhi *et al*., 2018). The anti-cancer properties together with anti-inflammatory effects and neuroprotective activities of citrus flavonoids have been extensively documented(Cirmi *et al*., 2016; Musumeci *et al*., 2020). The main flavanones detected in satsuma mandarin juice processing waste include naringin, hesperidin, hesperetin, neohesperedin and narirutin and rutin (Kim H & Kim M, 2016). Besides naringin and hesperidin, peels of citrus fruits also contain notable amounts of flavonoids. Research indicates that hesperidin and narirutin predominantly accumulate in the flavedo part of the peels and solid residues while liquid residues contain higher amounts of naringin and eriocitrin(Coll *et al*., 1998). Tests have indicated that Hesperidin levels exceed those of juice and seeds because fruit coloration likely depends on this compound's presence in peel. The naringin content reaches 90% levels in the peels and rags and pulp material while present at 0.02–0.03% levels in juice but hesperidin occurs at 0.015–0.025% in juice. A minor amount of phenolic acids exists within citrus fruit juice (Kim H & Kim M, 2016). These compounds exist as hydroxybenzoic acids (including gallic, vanillic and syringic acids) and hydroxycinnamic acids (consisting of caffeic, ferulic, p-coumaric and sinapic acids) which display distinguished free radical scavenging features (Kumar & Goel, 2019). Seeds that remain after juice extraction become a valuable source of oil combined with proteins and limonoids and offer significant amounts of the flavonoids eriocitrin and hesperidin together with phenolic compounds.

Citrus sinensis: The small evergreen tree known as Citrus sinensis (L.)Osbeck (sweet orange) stems from Southern China and Europeans discovered it during the sixteen and seventeenth century. The natural elements in orange fruits include vitamin C and secondary compounds such as flavonoids and carbohydrates and carbamates and alkylamines and carotenoids and volatile substances along with small amounts of calcium potassium sodium and magnesium (Favela *et al*., 2016). Processing of orange results in the production of food industry extracts and juices and candies. Orange juice exists as one of the most popular Citrus beverages worldwide which scientists have extensively researched for its health effects. Researchers investigated the antioxidant capacities of OJe extract along with OJe extract components using cell-free and cell-based experimental setups (Ferlazzo *et al*., 2015; Ferlazzo *et al*., 2016; Barreca *et al*.,2014; Barreca *et al*., 2016). Research has confirmed that OJe exhibits anti-inflammatory effect (Fusco *et al*., 2017; Cirmi *et al*. 2021) as well as anti-epileptic effect (Citraro *et al*., 2016) and anti-obesity effect (Montalbano *et al*., 2019) in animal studies while the orange EO demonstrated promising potential as an anti-anxiety agent(Guo *et al*., 2020).

The multiple phytochemical compounds found in C. sinensis peel extract particularly phenolic and flavonoid components contribute to its proven antioxidant effects (Liew *et al*., 2018). Studies have demonstrated that pectic oligosaccharides extracted from orange peel waste positively affect the growth of bifidobacteria and lactobacilli in human fecal inoculum fermentation experiments(Gómez *et al*., 2014). Analyzing discarded seeds of Hamlin, Natal, Perario and Valencia orange varieties reveals their potential for essential oil extraction along with high contents of carotenoids, phenolic compounds, tocopherols and phytosterols acting as main factors for free radical scavenging capacity in this by-product(Jorge *et al*., 2016). Research proves that orange seed oil as well as non-oil extracts demonstrate noteworthy antibacterial and antifungal properties alongside their antioxidant abilities for developing antimicrobial medications(Oikeh *et al*., 2020).

***Citrus reticulata* and *C. reticulata* hybrids:** Chinese C. reticulata Blanco (Ponkan) peel stands as a waste material in the industry. Research conducted using hydrodistillation yielded EO from Blanco peel while limonene (89.31%) comprised the principal component and demonstrated antimicrobial efficacy against Cutibacterium acnes together with standard microorganisms S. aureus, B. subtilis and E. coli (Hou *et al*., 2019). Agricultural waste emerges as by-products from the food industry processing of “satsuma mandarin.” The high concentration of polyphenols in fermented Citrus by-products stands as the basis for strong antibacterial and antilisterial activity against E. coli and Listeria monocytogenes (Kim *et al*., 2017). Studies also show that EO from C. reticulata peel exhibits wound healing property through its ability to reduce skin lesion dimensions in vivo (Ishfaq *et al*., 2021). Research shows that Mandarin peels contain higher total flavonoid content than lemon and grapefruit peels and display medium levels of cytotoxicity toward the HL-60 cell line serving as an experimental model for acute myeloid leukemia (Diab *et al*., 2016). Interestingly, a flavonoid-rich extract of C. reticulata juice showed promising anti-cancer activity in anaplastic thyroid carcinoma cell lines(Celano *et al*., 2015), as well as proved to be a strong neuroprotective agent in an in vitro model of Parkinson’s disease (Cirmi *et al*., 2021). it showed anti-angiogenesis effects by counteracting tube formation of HUVECs endothelial cell line and cell cancer migration through downregulation of matrix metalloproteinase-9 (MMP-9) expression in MDA-MB-231 cells, thus revealing a potential therapeutic agent in triple-negative breast cancer metastasis (Park *et al*., 2016). Experimental research demonstrated that “satsuma mandarin” peel extract following juice processing stopped pancreatic cancer cell growth through apoptotic mechanism activation and prevented cell movement by triggering signaling pathway proteins MKK3/6 and P38. Studies revealed that this extract generated anticancer effects when tested with a xenograft experimental model. The analytical study performed through computer modeling confirmed that flavonoids naringenin and hesperetin play an essential role in the anticancer activity displayed by this fermented extract (Lee *et al*., 2018).

The research team isolated quercetagetin as a radical scavenger from “satsuma mandarin” peel powder methanolic extract which demonstrated its ability to decrease ROS levels and protect Vero cells from H_2O_2-induced DNA damage (Yang *et al*., 2011). The procedure for extracting juice from Citrus junosSiebold ex Tanaka (yuzu) results in seed disposal. Laboratory tests revealed that this waste product contains abundant limonoidaglycone substances and oils as well as glycosides which displayed antioxidant properties coupled with radical scavenging potential (Minamisawa *et al*., 2014). Many studies indicate that the leaf fraction of Murcott mandarin (C. reticulata × C. sinensis hybrid) protects the stomach against alcohol-induced gastric ulcers in rats through its known anxiolytic, anti-inflammatory, antioxidant and anti-apoptotic chemical properties (Hamdan *et al*., 2020). EA extraction from C. reticulata Blanco Santra cultivar leaf and fruit peel decreases LPS-stimulated TNF-α and NO levels in RAW 264.7 cells thus demonstrating their anti-inflammatory properties (Hamdan *et al*., 2016). Clementine by-products containing leaves and peels demonstrate anti-oxidant properties for decreasing the risk of type 2 diabetes and obesity-related diseases according to research by (Leporini *et al*., 2020).

Fig 5. Picture for dried Peel, pulp, seed collected from orange

Other industrial applications of Citrus phytochemicals

Food Industry

Studies demonstrate that essential oils found in citrus peels maintain several functional uses that span across the food preservation sector and food safety domain as well as the nutraceutical industrial field. Essential oil (EOs)-based thin films alongside microencapsulation utilizing nanoemulsion coatings and biodegradable polymers and spray applications and the antibacterial action mechanism of the active chemicals present in EOs are outcomes of different research (Mahato *et al*., 2019). The use of citrus essential oils (CEOs) exists in multiple applications across the cosmetic industry and pharmaceutical sector and food production area and packaging manufacturing sector. CEOs offer multiple applications throughout food preservation together with packaging solutions and storage management according to (Bhavaniramya *et al*., 2019). Multiple studies have shown that essential oils sourced from tea tree oil, cinnamon oil, sesame oil and clove oil, lemon oil, chia oil, and thyme oil demonstrate enhanced antioxidant and antibacterial activity and improve cereal storage life and food security (Khalid *et al*., 2023). Terpenes along with aromatic volatile compounds operate as essential components for food safety systems though they maintain food quality standards. EOs display multiple benefits that allow them to function as antibacterial agents and antioxidants thus serving as chemical preservative substitutes which help maintain fresh foods from cereals and vegetables (Bhavaniramya *et al*., 2019).

Numerous food production facilities must overcome a significant waste problem since they need to control and maximize utilization of discarded resources. The food industries together with food scientists employ food wastes as protective coating materials which safeguard food products against environmental elements. The market has widely accepted food coatings and films due to their palatable properties and biodegradable nature alongside their beneficial storage effects that protect food quality. The examination of polysaccharides as suitable food film materials began during the last ten years. Food safety applications showed polymeric materials hold great yet unrealized potential for microbiological uses in the industry. In a study, essential oils (EOs) were mixed with polysaccharide matrices to further enhance the functional qualities of edible films (Anis *et al*., 2021).

The exhausted CF peel material contains pectin and dietary fibers resembling the fiber content found in juice and pulp (Waghmode *et al*., 2018). The natural gel-forming substance exists in complex or insoluble forms between white and light brown colors. Pectin functions as a thickener and stabilizer and emulsifier and texturizer in the preparation of confectionery products and jams and jellies along with biodegradable items. Pectin serves as a stabilizer agent for acidified milk beverages and yogurts. Research studies have confirmed that acidified milk beverages experience protein clustering and whey separation because stabilizer agents are not present. The addition of citrus pectin acts as a protective colloid to prevent milk drinks from showing destabilization behavior according to Naseri *et al*., (2008). Romero-Lopez *et al* (2011) performed research to explore how citrus fiber affected muffins. The experimental muffins obtained through addition of dietary fiber-rich orange bagasse product (DFROBP) achieved fiber content levels which were 40 and 63% higher than in reference muffins. Combining wheat flour with DFROBP allowed the creation of baked goods containing elevated amounts of dietary fiber together with a significant indigestible fraction deemed suitable for different kinds of dietary needs.

Cosmetic Industry: The numerous studies have proved citrus waste extract bioactivity whereas actual application in cosmetics remains rare which demands more intense research. Research should proceed toward developing safe extract dosages for cosmetics while evaluating multiple quality indicators for the formulations including basic physics and chemical qualities and stability tests and consumer readiness evaluations. Ethanolic extracts of Citrus unshiu waste showed multiple favorable activities as reported by (Kim *et al*., 2008). Use of this extract presents possibilities for application in cosmetic products designed to counteract acne and achieve skin brightness. The antibacterial activity of the extract against acne bacteria Propionibacterium acnes was moderate yet the extract showed no adverse impact on normal microorganisms of the skin. The anti-collagenase and anti-elastase properties of C. reticulata Blanco extract peel make it suitable for developing anti-aging cosmetic products (Apraj& Pandita, 2016). The EC50 values demonstrated hot extract and macerated C. reticulata Blanco peel inhibited collagenase and elastase with 329.33 µg/mL and 466.93 µg/mL as well as 3.22 mg/mL and 5.09 mg/mL. The investigators determined significant anti-radical abilities of the extract towards 1,1-diphenyl-2-picrylhydrazyl (DPPH) combined with superoxide anion and 2, 2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) radicals. Centuries of folk medical practice has led to widespread use of citrus essential oils for their favorable fragrance and antibacterial properties which currently powers aromatherapy applications and conditions products like air fresheners and cosmetics. The contents of essential-oil components in citrus essential oils that are used in skincare products are regulated by legislation because they might have adverse effects which include phototoxicity and allergenicity. Nevertheless, these oils offer multiple beneficial effects for skincare including skin degreasing, antiseptic purposes along with skin brightening and astringent properties. Research shows that citrus essential oils cause phototoxic reactions because of furocoumarins in these oils that strongly absorb UV light and produce burns along with inflammation and swelling in the skin. The formulation of a mosquito-repellant cream required lemon-grass (Cymbopogon citrus) essential oil for its safety functions while maintaining its citrus aroma according to Jayarathna *et al*. (2018). In this experimental study volunteers received test treatment and commercial herbal cream exposure to three types of mosquitoes called Aedesaegypti, Anopheles stephensi and Culexquinquefasciatus for 240 minutes. Research used C. sinesis L. California Navel orange-peel extract for facial-cream formulation since this extract exhibited a high level of anti-tyrosinase activity (IC50 = 255.10 µg/mL) (Wuttisin *et al*., 2021). A sensory analysis panel found the facial cream with 2% (w/w) orange-peel extract to be pleasant for use. The clinical study revealed that the formulated product decreased melanin pigment by 17.33% in 20 volunteers during one month of use without causing any skin irritation (Wuttisin *et al*., 2021).

Biofuel Production: Citrus waste undergoes essential oil and pectin and polyphenolic compound extraction to enable various biotechnological methods for valuable product creation into marketable goods while acting as critical elements of biorefinery systems (Ortiz-Sanchez *et al*., 2024). During the previous decades bioethanol grew into one of the top contenders to replace gasoline transportation fuel. Bioethanol results from yeast processing of sugar substances. The cellular structure of citrus by-products requires pretreatment so that long polysaccharides become short fermentable sugars. The research conducted by Sarkar *et al*., (2024) showed fresh materials produced lower quantities of ethanol (2.0–2.7 gL^{-1}) than distillation dealt with by-products (3.9–7.9 gL^{-1}). Extraction of polyphenolic compounds did not modify the cellulose percentage in relation to fresh material so researchers assume that limonene and phenolic compounds may have restricted the outcome. The elimination of limonene components during distillation processes allowed distillated orange peel to yield 2.5 times more ethanol (7.89 gL^{-1}) compared to undistilled peels. The antimicrobial quality of limonene necessitates removing essential oil from the process before fermentation takes place according to Patsalou *et al*. (2019) and Sarkar *et al*. (2024). Acid hydrolysis stands as the most frequently used pretreatment method but researchers have documented additional procedures. The fermentation process starts after completing the pretreatment procedure. The identification of Saccharomyces cerevisiae stands as the leading microorganism for producing bioethanol throughout research studies. The bioethanol production process was evaluated by (Patsalou *et al*., 2019) through the use of three yeast strains which processed orange peel wastes following dilute acid hydrolysis (5% of H_2SO_4) at various thermal temperatures (108, 116, 125 °C). P. kudriavzevii demonstrated the highest ethanol production at 5.8 gL^{-1} when the researchers utilized waste produced through 116 °C pretreatment maintained for 10 minutes.

The authors reported that adding an enzymatic pretreatment step to the process augmented ethanol yields from total sugar consumption of 0.32 g EtOH•gTSC−1 to 0.42 g ETOH•gTSC−1 which produced 9.2 g•L−1 ethanol. The recycling process water generated a three-fold elevation that produced 30.7 g•L−1 of ethanol product concentration. Saadatinavaz *et al*. (2021) studied the combined process of ethanol production followed by biogas generation according to their research findings. The researchers obtained biogas from anaerobic fermentation processes that yielded 60 to 70 percent methane levels according to their experimental methods. After performing anaerobic digestion of enzymatically pretreated orange waste residues at 100 °C for 30 minutes researchers obtained the highest methane yield of 162 NmL•g−1 volatile solids after 45 days. The biomass without pretreatment produced biogas with 194 NmL•g−1 volatile solids yields because the enzymatic hydrolysis combined with pretreatment processes eliminated hemicellulosic sugars and other degradable compounds from the biomass. Production of volatile fatty acids (VFAs) with 2–6 carbon atoms constitutes fundamental carboxylic acids that industry has adopted extensively for multiple food and farming applications. Researchers examined citrus wastes as production material for volatile fatty acids through biorefinery methods recently. Rizzioli *et al*., 2024 undertook studies on orange peels valorization at laboratory dimensions. The research demonstrated that by-product of orange peel production showed promising potential to yield VFAs (acetic and formic acids) at a 43% VFA yield per gram total orange peel solids through continuous agitation. This method had a higher operational efficiency because it processed low solid concentrations (10%) and finished fermentation within 5 days which made it ideal for biorefinery applications. Biofuel consists of transesterified mono-alkyl esters obtained from animal fats and vegetable oils as per Cruz *et al*. (2020). The source functionality of citrus wax includes polyphenolic compounds while FAMEs (fatty acid methyl esters) production makes up its raw material potential. The acid transesterification process of citrus wax resulted in FAME production at a rate of 3.03% according to (Cruz *et al*., 2020). The obtained biodiesel contains hexadecanoic acid methyl ester at a concentration of 0.32% among all identified compounds derived from this by-product. The study of citrus waste usage for biodiesel creation has been revealed but present research remains primarily exploratory.

Commercialization of Citrus fruit based products: Bioactive compounds (BACs) including flavonoids and essential oils and carotenoids with pectin are used in multiple industries including food production and pharmaceuticals and cosmetics as well as agriculture. The commercial value of these compounds enables product innovation because of their various antioxidant and antimicrobial and health-promoting properties. Market data suggests the citrus essential oil market will surpass $6 billion by 2025 because businesses continue to seek natural preservatives and nutraceuticals. The review examines commercial citrus bioactive products as well as their industrial applications and their positive impact on sustainable economic expansion.

Food Industry Innovations: The preservation of food and its fortification along with packaging rely on citrus bioactives in the food sector. Apeel Sciences along with other companies developed essential oil-infused edible films which incorporate orange peel extracts into biodegradable coatings that minimize postharvest losses in fruits according to Maqbool *et al*. (2023) and Nieto *et al*. (2021). Small-sized citrus fiber pieces derived from pomace receive commercial use as baked goods fat replacement agents and moisture binding additives. Fiberstar, Inc. commercializes Citri-Fi® which is a citrus fiber product aimed at gluten-free breads and plant-based meats through exploitation of its water-retention and emulsifying characteristics (Maqbool *et al*., 2023; Nieto *et al*., 2021). The beverage sector includes citrus polyphenols as functional ingredients by launching Valencia orange peel extract-enriched antioxidant juices targeted toward health-minded consumers (Hannah *et al*., 2023; Saini *et al*., 2022). Food products can now use citrus carotenoids β-cryptoxanthin and lutein instead of synthetic colorants because they meet clean-label demands through their yellow-orange color effect and pro-vitamin A properties (Saini *et al*., 2022; Nieto *et al*., 2021).

Pharmaceutical and Nutra-ceutical Formulations: Several compounds derived from citrus serve as essential agents in developing drugs as well as nutraceuticals. The furanocoumarin compound bergamottin from grapefruit faces regulatory hurdles for its use in improving drug bioavailability through cytochrome P450 inhibition because of possible herb-drug complications (Khan *et al*., 2021; Saini *et al*., 2022). The pharmaceutical industry commercializes standardized citrus flavonoid extracts through the sales of Diosmin which functions as a hesperidin derivative when prescribed to treat chronic venous insufficiency with annual revenue surpassing $500 million (Hannah *et al*., 2023; Saini *et al*., 2022). Industrial extraction of polyphenol-enriched extracts from citrus waste plays a significant role in the nutraceutical sector as FutureCeuticals produces Citrus Bioflavonoids Complex which supports immune function using orange and grapefruit peels (Nieto *et al*., 2021). Weight management supplements are now using bitter triterpenoids called limonoids which exist in seeds and membranes as functional components. NutraGenesis implements Limoninglucoside in their formulations which this patented derivative utilizes for lipid metabolism control according to Hannah *et al*. (2023) and Saini *et al*. (2022). Limonoids together with citrus carotenoids represent fast-growing food ingredients because annual market demand increased by 8–10% since 2020 according to Saini *et al*. (2022) and Nieto *et al*. (2021). The enzymatically produced Modified citrus pectin (MCP) functions as an oncology supplement because it demonstrates anti-metastatic properties. MCP serves as a complementary cancer treatment for breast and prostate cancer according to EcoNugenics and other companies since preclinical studies highlight its ability to inhibit galectin-3 (Hannah *et al*., 2023; Saini *et al*., 2022).

Cosmetic and Personal Care Products: The cosmetic industry utilizes citrus essential oils as well as antioxidants for their skincare and fragrance applications. L'Occitane en Provence uses lemon essential oil in Brightening Hand Cream to achieve skin-brightening properties based on the citral content found in the oil (Hannah *et al*., 2023; Saini *et al*., 2022). Owners of The Ordinary product line use citrus peel extracts with ferulic acid and vitamin C in their anti-aging serums which help minimize oxidative stress in targeted areas. Natural cosmetics represent a market worth $38 billion in 2023 and their citrus-based components account for 15% of this expansion since consumers seek environmentally friendly natural ingredients (Maqbool *et al*., 2023; Nieto *et al*., 2021). The therapeutic property of citrus oils for calming anxiety and brain protection enables doTERRA and Young Living to use cold-pressed citrus extracts for evening diffuser moods and topical treatments.

Agricultural and Environmental Applications: The utilization of citrus waste leads to biofertilizer and biopesticide production which replaces synthetic agriculture chemicals. The biofertilizer and biopesticide company Terrafertil produces orange peel compost which contains flavonoids and terpenes to improve soil microbiota and fight phytopathogens as stated by Hannah *et al*. (2023) and Nieto *et al*. (2021). Organic pesticide manufacturers utilize citrus limonene to create EcoRaider®'s Ant & Crawling Insect Killer by leveraging D-limonene's lethal impact against insects. The waste management strategies and biopesticide product development by citrus processing plants produce dual financial benefits because the biopesticide sector could grow to a $10 billion industry by 2027 (Hannah *et al*., 2023; Maqbool *et al*., 2023).

Economic Dynamics and Market Trends:

Cost-Benefit Analysis of Waste Valorization: Waste from the citrus processing industry amounts to 50–60% of total weight since it consists mainly of peels and seeds. Valuing waste, to create bioactive compounds, results in doubled profits because it lowers disposal expenses while producing premium items. While production of D-limonene from orange peels requires between $5 to $10 per kilogram, companies recover profits through high market prices of $20 to $30 per kilogram of the essential oil (Hannah *et al*., 2023; Maqbool *et al*., 2023). The commercial price of retail citrus pectin varies between $25–$40 per kg but its production from pomace requires investments of $8–$12 per kg (Nieto *et al*., 2021). The financial dynamics of essential oil and pectin and biofuel production encourage multi-product biorefinery operations that extract different materials from single waste streams to reach highest resource efficiency rates (Hannah *et al*., 2023; Nieto *et al*., 2021).

Global Market Valuation and Growth Projections: The citrus bioactive market globally demonstrates projected annual growth of 6.8% from 2023 through 2030 because natural additives and functional foods have gained increased consumer demand. The market consists of essential oils at 40% while pectin holds 25% and flavonoids make up 20% (Maqbool *et al*., 2023; Saini *et al*., 2022). The citrus pectin production in Europe is controlled by CP Kelco and Herbstreith& Fox who operate as dominant market players by having 70% of the market share. Nutcacoorestablishment in North America drives the region to be the largest market for citrus flavonoids (Nieto *et al*., 2021). Brazil together with India invests in facilities to process citrus waste into valuable products because Brazil annually produces 20 million tons of citrus (Hannah *et al*., 2023; Saini *et al*., 2022).

Sustainability and Circular Economy Contributions: The conversion of citrus waste into valuable products through valorization fits circular economy practices because it decreases environmental damage and increases financial benefits. The conversion of 1 million tons of citrus waste into bioactive compounds at Florida's processing facilities produced $200 million per year which resulted in 30% reduction of operational expenses (Hannah *et al*., 2023; 5). Studies of life cycle assessments demonstrate that citrus-based packaging films cut carbon emissions in half thus drawing attention from investors focused on ESG factors (Maqbool *et al*., 2023). Government support for this practice exists through the EU's Horizon 2020 fund which finances citrus biorefinery projects as part of their 2030 target to maximize waste utilization to 90% (Nieto *et al*., 2021).

CONCLUSION

Even though citrus seeds have a valuable and potential reservoir of phytochemical composition, the idea of recycling and valuing them is still undervalued in comparison to peels. The economic value of recycling seeds to create goods with extra value has been demonstrated. For example, because of its high oil yield and essential fatty acids, mandarin seed oil (*C. reticulata*) was an excellent source for the manufacturing of edible vegetable oils and biodiesel. The antioxidant and antibacterial qualities of citrus plants were enhanced by these bioactive ingredients. Due to consumer pressure to create new products with less synthetic preservatives and produced using eco-friendly and sustainable methods, the food industry is one of the sectors that uses various extracts made from citrus co-products. In this situation, citrus co-products could be a good substitute to create sustainable and healthier products.

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All authors declare that this research article is original and has not been published elsewhere in any form or language (partially or in full).

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Author contributions

Priyanka Singh (as supervisor) has contributed to the study conception for medicinal importance of citrus plants. Chhavi Acharya (as research scholar), Prakash kumar (student), Aditi singh (student) has contributed for collecting relevant information, compiling and writing of this review article. They have written first draft of the manuscript and priyankasingh (as corresponding author), has read and approved the final manuscript.

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