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Bridging sustainability and industry through resourceful utilization of pea pods- A focus on diverse industrial applications

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ABSTRACT

The focus on sustainable utilization of agricultural waste is currently a leading area of scientific research, driving significant advancements in technology and circular economy models. The fundamental capacity of bio-based products, bioprocessing techniques, and the crucial involvement of microbial treatments are opening opportunities for efficient solutions in various industries. One of the most popular green vegetables, peas are members of the Fabaceae family and have a pod-like structure. Every year, a significant amount of pea pods is discarded as waste products of peas that have negative impacts on our environment. In this comprehensive review, we explore innovative methods for utilizing pea pods to minimize their environmental footprint and optimize their viability across multiple industries. A large portion of the pea processing industry's output consists of pea pods. Variety of proteins, with major classes being globulin and albumin (13%), dietary fiber (43–58%), and minerals are abundant in these pods. Because of their diverse physiochemical properties, they find applications in many diverse fields. The porous pea pods comprised cellulose (61.35%) and lignin (22.12%), which could make them superior adsorbents. The components of these byproducts possess valuable attributes that make them applicable across treatment of wastewater, production of biofuels, synthesis of biocolors, development of nutraceuticals, functional foods, and enzymes for the textile industry, modification of oil, and inhibition of steel corrosion.

1. Introduction

Vegetable waste is produced in large amounts every year all across the world, especially in developing nations like Pakistan. These losses include important qualitative losses, such as critical nutrients and different bioactive substances, in addition to quantitative losses. The effective management of waste becomes essential to addressing these issues, allowing the extraction of essential nutrients for later use (Ahmad et al., 2023; Akbar et al., 2023; Akhtar et al., 2023; Bangulzai et al., 2022; Mohammad, Kamil, Tawfeeq, & Ahmed, 2023; Nawaz et al., 2022; Okonkwo & Achilike, 2022; Sultan, 2023). These beneficial waste byproducts act as natural sources of phenolic chemicals and antioxidants (Abbas & Alkheraije, 2023; Ahouangninou et al., 2022; Ara, Arshad, Faheem, Khan, & Shakir, 2022; Mickdam, Alwaleed, Madany, & Sayed, 2022; Moseri, Umeri, Onyemekonwu, & Belonwu, 2023; Rossi & Efendi, 2022; Tahir, Khan, Ashraf, & RDN, A.I., Mubarik, U., 2023; Widowati et al., 2022).

Peas are among the earliest domesticated plants and the world's second-most-cultivated legume. Their low cost, extensive global distribution, and ease of growing are some of their advantages. It is worth mentioning that around 35–40% of the total pea weight comes from the outer pod. Large amounts of residual pea material are produced worldwide, and a large portion of it is used as animal feed (Nasir, Zaidi, Siddiqui, & Sirohi, 2023). It is noteworthy that out of the annual global pea production that is approximately 11.7 million tons, a substantial 4 million tons consist of pea pods, which are typically discarded as waste

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(Demirhan, 2020). Pea pods are the main waste products of peas and due to a lack of awareness and locally available waste processing facilities, the pea pods or husks, constituting 55% of the total volume of freshly harvested green peas, have traditionally been relegated to the status of under-utilized waste by-products. There are several reported applications of pea pods, including making cellulolytic enzymes, adding them to animal feed, and using them as a feedstock for ruminants (Kumari & Deka, 2021). A range of bioactive compounds have been identified in pea pods, including 5-caffeoylquinic acid, epicatechin, and hesperidin, these compounds have been associated with various health benefits, including antioxidant and anti-inflammatory properties (Castaldo et al., 2022). The phenolic compounds found in pea pods contain antioxidant characteristics that can effectively scavenge free radicals such as, superoxide, hydrogen peroxide, and nitric oxide radicals. This gives the plant resistance to oxidative damage and degradation caused by free radicals (Abd El-Galil, Negm El-Dein, Awad, & Helmy, 2021). By-products derived from legumes generally exhibit higher levels of dry matter digestibility, resulting in an increased availability of energy for metabolic processes. According to Tassoni et al. (2020) the use of these by-products primarily serves two main goals: improving the dietary profile and reducing the presence of anti-nutritional elements. Agricultural residues have a lot of potential as adsorbent materials because of their physicochemical characteristics and affordability. These agricultural waste products are primarily made up of lignocellulosic materials like lignin, cellulose, and hemicelluloses (Demirhan, 2020). The pea peels biomass has been transformed into pea peel-activated carbon (PPAC) that is a novel biochar used for an eco-friendly management of waste in various sectors. Biochar, defined as carbon-rich solids generated through the gasification or pyrolysis of biomass at temperatures exceeding 300 °C in a nitrogen-rich environment is gaining prominence as a cost-effective and environmentally advantageous alternative to expensive adsorbents (El-Nemr, Abdelmonem, Ismail, Ragab, & El Nemr, 2020). In addition to its economic benefits, biochar also provides advantages such as the reduction of secondary environmental pollutants, it is renewable, and of high-quality biosorbent (Liu, Zhang, Li, Feng, & Zhang, 2014). Pea peels are effective at removing cationic and anionic contaminants from solutions because of their inherent surface charge properties (El-Nemr, Abdelmonem, Ismail, Ragab, & Nemr, 2020). One common, practical, and inexpensive option is to utilize adsorbents made from agricultural and horticulture waste to filter pollutants out of industrial effluent. With the additional benefit of reusing these horticultural and agricultural adsorbents, this method provides a sound base for developing wastewater treatment systems (Sharma & Ayub, 2019). In addition to their application in wastewater treatment as an adsorbent for pollutants, biodegradable horticulture, and agricultural waste products play an essential role in the management of agricultural waste (Sharma & Ayub, 2019).

Agricultural byproducts are rich in bioactive compounds, including terpenoids, polyphenols, alkaloids, and tannins, which have antioxidant, anti-inflammatory, and other beneficial effects (Sorrenti, Burò, Consoli, & Vanella, 2023). These compounds can be used as low-cost adsorbents for the removal of potentially toxic elements from wastewater, with high efficiency and bioadsorption capacity (Ungureanu et al., 2023). Additionally, phytochemicals derived from these byproducts have valuable properties, such as antioxidant, antimicrobial, and anti-cancer activity, and can be applied in various industries, including pharmaceuticals, food production, and wastewater remediation (Oleszek, Kowalska, Bertuzzi, & Oleszek, 2023). Owing to their adsorption capabilities, agricultural byproducts contain an extensive number of chemicals with the potential to have biological effects (Naqvi et al., 2021). Food waste possesses significant nutritional potential; but, due to consumer behavior and preferences, it is often intentionally discarded. The issue of food insecurity arises from the combination of rising food waste and aggravated food scarcity, both of which originate from the continuous expansion of the global population (Rudra et al., 2020). Efficient management of pea pods as food waste products is a crucial concern, due to their high levels of dietary fiber and other nutritionally beneficial components, such as proteins and minerals (Hanan, Rudra, Sagar, & Sharma, 2020). Utilizing pea pods as a dietary fiber source to enhance the nutritional value of food, including incorporating them into buckwheat-enriched bread, provides an efficient method to supply both dietary fiber and essential micronutrients in staple diets (Tassoni et al., 2020). Pea pods contain minerals, dietary fibers, organic acids, phenolic compounds, colors, and sugar derivatives in reasonable amounts and most of these bioactive chemicals have beneficial health characteristics, such as antibacterial, anticancer, antiviral, antimutagenic, and cardio-protective effects (Naqvi et al., 2021). Previous reviews on the related topics have described the applications of pea pods in different sectors as combined with other fruit and vegetable waste products. This review mainly focusses to explore the valorization of pea pods only in a comprehensive way so that the researchers may find future research directions to utilize this valuable waste ingredient for sustainable development in different sectors.

2. Applications of pea pods as valuable waste products

Industrial processing of peas generates a significant amount of trash, which presents significant environmental problems and may cause the release of hazardous gases. Inadequate and unsustainable waste disposal practices can result in significant economic burdens, directly impacting the profitability of production operations (Tassoni et al., 2020). Pea waste has vast utilization in different fields as a summary of it is given in Table 1.

2.1. Water pollution remediation

The unprocessed effluent released by the textile industry has significantly compromised the quality of freshwater and poses serious hazards to public health (Tebeje, Worku, Nkambule, & Fito, 2020). This alarming issue is exacerbated by the widespread use of hazardous dyes in coloring acrylic, nylon, wool, and silk fabrics as investigated by Dod et al. (2012) and natural breakdown of these compounds is difficult, so activated carbon adsorption is employed (Amelia & Salamah, 2019). The conventional techniques for pollutant removal such as chemical precipitation, ion exchange, and commercial activated carbon adsorption have become unaffordable. Fortunately, recent research by Sahlabji et al. (2022) has unveiled a cost-effective solution, the utilization of activated carbon derived from green pea peel (GPP) for the efficient adsorption of dyes and metallic ions. Taher (2019) reported that the uptake of methylene blue (MB) dye by pea peels was faster than that of commercial activated carbon due to the higher pore diameters of pea peels than those of commercial activated carbon. Surface chemistry of pea pod's activated carbon plays a crucial role in adsorbing contaminants from wastewater (Fayomi, Olukanni, Fayomi, Joseph, & Popoola, 2016). Activated carbon adsorbs pollutants through a mechanism known as physical adsorption, which is based on the attractive forces between the adsorbent surface and the pollutant molecules. Dhawan, Kumar, Kaur, & Choudhary (2017) explored the importance of activated carbon's large specific surface area and high degree of surface reactivity in removing organic pollutants from water. The role of pore diffusion in the adsorption process was also emphasized by Delpeux-Ouldriane et al. (2016). Activated carbon derived from carbonization of the pea pods has a high surface area with a network of pores and a large internal surface area, which provides ample sites for adsorption to occur. Batch adsorption experiments were commonly conducted to evaluate the efficiency of an adsorbent material in removing contaminants, such as dyes, from a liquid solution. A dye solution that is used as a representative of wastewater, is prepared and mixed with the adsorbent. Sampling and analysis track dye concentration changes over time using techniques like UV/Vis spectrophotometry. Parameters such as adsorption capacity are evaluated to optimize the process for efficient dye removal (Шайхиева, Фридланд, & Свергузова, 2021). Sahlabji et al.

Table 1
Application of pea waste across various sectors.

Pea waste utilization	Biochemical characteristic	Functions	Conditions	References
Water treatment	Green pea peel derived and acid-treated carbon (GPP-AC)	Adsorption of methylene blue	adsorption of 163.94 mg MB/g GPP- AC at 30 °C	(Dod, Banerjee, & Saini, 2012)
	Cellulose Nano crystals (CNCs)	Nano composite hydrogel was used for the removal of methylene blue dye	Toform Pectin-PAAc/CNC Nano composite by γ-irradiation.	(Al-Gorair, Sayed, & Mahmoud, 2022)
	Unmodified biochar (Pea-BO) and modified biochar (Pea-BO-NH_2)	Adsorb copper (II) from aqueous medium	–	(El-Nemr, Abdelmonem, Ismail, Ragab, & El Nemr, 2020)
	Pea pods as a low-cost adsorbent	Removal of reactive blue 19 dye	pH 2, temperature: 35 °C and adsorbent amount of 1.5 g/100 mL	(Demirhan, 2020)
	MPAC-500 and MPAC-600 (magnetic-activated carbons synthesized from the pea peel pyrolyzed at 500 and 600 °C, respectively)	Adsorb arsenic (As) from aqueous solutions	Temperature: 500 °C and 600° C	(Sahu et al., 2022)
	Laccase from agro-residues waste (potato peel, banana peel, sawdust, pea peel) by *Bacillus aquimaris* AKRC02	Remediation of various environmental pollutants	(Incubation time: 120 h with culture amount of 4.58 U/mL), 35 °C; 6.624 U/mL) and pH 7.0; 10.142 U/mL) and nutritional sources (glucose 1.0%; 14.164 U/ mL and peptone 0.5%; 18.124 U/mL)	(Kumar, Singh, Bilal, & Chandra, 2021)
	Biochar-SO prepared from pea peel	Remove Cr^{6+} ions from the aqueous solution	Optimum pH 1.48	(El-Nemr, Yılmaz, Ragab, & El Nemr, 2022)
	The pea waste loaded with zirconium is used as an engineered biochar	Adsorb fluoride from aqueous solution.	0.001 N NaOH	(Swain, Patel, Panda, Patnaik, & Dey, 2019)
	Pea pod peel (agro-industrial) waste	adsorb pollutant Cr (VI) from wastewater	_	(Sharma & Ayub, 2019)
	unmodified (Pea—B) and modified (Pea-BO-NH2 and Pea-BO-TETA) biochars derived from the pea peel	adsorb Acid Orange 7 (AO7) dye	pH 2 contact time 3 h	(El-Nemr, Abdelmonem, Ismail, Ragab, & Nemr, 2020)
Product development	Dietary fiber, proteins, and minerals.	Developing instant pea soup powder (IPSP)	-	(Hanan et al., 2020)
	Insoluble and soluble fiber in pea pod powder	Source of fiber in buckwheat enriched bread (20%)	Proof at 40 °C and 95% RH for 60 min and bake at 190 °C for 45 min	(Hanan, Rudra, Sharma, Sagar, & Sehgal, 2021)
Product development	Protein from pea peel	Dehydrated green curd of pea peel (DGCPp) with high protein content (35%) incorporated into snack crackers and instant soup powder		(Mousa et al., 2021)
Nutraceuticals	5-caffeoylquinic acid epicatechin, hesperidin (polyphenols)	Suitable nutraceutical formulation to vehiculate the active compounds	_	(Castaldo et al., 2022)
	Pea hull Fiber (PHF)	Help older adults achieve fiber recommendations	_	(Alyousif et al., 2020)
	Polyphenols flavonoids	Antioxidant antimicrobial	1,1-diphenyl-2-picrylhydrazyl (DPPH) assay, ferric reducing (FRAP) assay and 2,2 azinobis 3-ethylbenzo-thiozoline-6- sulfonic acid (ABTS) assay	(Hadrich, El Arbi, Boukhris, Sayadi, & Cherif, 2014)
	Saponins	The hemolytic activity of the saponins was analyzed directly on blood-gelatin covered TLC plates.	50 °C and 60 °C 24 h	(Reim & Rohn, 2015)
	Phenols, flavonoids	Antioxidants, Antimicrobial	_	(Naqvi et al., 2021)
	Twenty polyphenolic compounds, mainly flavonoid glycosides such as quercetin, kaempferol apigenin, and phenolics compounds	Attenuates DOX-induced oxidative myocardial injury.	5 mL/kg dist. Water containing 1% dimethyl sulfoxide. 5000 mg/kg of *P. sativum* extract for 24 h.	(Abdelghffar et al., 2021)
	Sulfated extract of pea peel extract	Anticoagulation, fibrinolytic, antioxidant, antiproliferative and prebiotic activity	HCl (pH 3), water (pH 7), or NaOH (pH 12) at 80 °C for 3 h. 100 g of dried pea powder.	(Abd El-Galil et al., 2021)
Biofuel	Holocellulose content 32.08% of cellulose 21.12% of hemicellulose	Biobutanol production	60–120 °C	(Nimbalkar, Khedkar, Chavan, & Bankar, 2018)
	Maximum glucose from Pea peel	To produce bioethanol	acid load; 1.0, 1.5, 2.0%, 15, 30 and 45 min. 100, 110 and 120 °C	(Rehman et al., 2015)
	Pentosans	Produce furfural	160 °C	(Yadav, Ghosh, & Ray, 2017)
Nutrition	Water soluble polysaccharides Predominant sugar(sucrose)	Emulsifying capacity Antioxidant Natural functional additives for different types of foods	80 °C,50 °C,20 °C, centrifugation for 15 min at 6000 ×*g*.	(Shehata, Darwish, & El-Sohaimy, 2020)
Food industry	Low-methoxylated pectin.	Dietary fiber with high water-binding properties can prevent staling in bakery products	1 L of 80% (*v*/v) ethanol,60 °C,1 h oven dried at 30 °C, 2 h,24 h in desiccator at RTP	(Gutöhrlein, Morales-Medina, Boje, Drusch,

(*continued on next page*)

Table 1 (*continued*)

Pea waste utilization	Biochemical characteristic	Functions	Conditions	References
				& Schalow, 2020)
Rheology	PHF	Water retention capacity	35 °C	(Martins et al., 2017) (Morales-Medina, Dong, Schalow, & Drusch, 2020)
Nutrition	Rhamnogalacturonan-I xylogalacturonan xyloglucan	_	Aqueous citric and malic acids (0.2%) at 100 bar between 125 °C and 155 °C	(Ramirez, Temelli, & Saldaña, 2021)
Oil modification	Pea hull (PH) and the epidermal cell wall (PCW	Rheological modifiers of an oil	Absorption index set to 0.1	(Calabrese, Gunes, & Farrés, 2021)
Extraction	Pectic polysaccharide homogalacturonan, xylo- galacturonan rhamnogalacturonan	_	pH 2, 70° C	(Gutöhrlein, Drusch, & Schalow, 2020)
Nutrition	trans-lutein chlorophylls a and b carotenoid pheophytin	positive effects on health outcomes	_	(Marles, Warkentin, & Bett, 2013)
	carotenoid production from *Rhodotorula mucilaginosa*	Bio-active compound having antioxidant property	pH 6.1, temperature 25.8 °C and agitation 119.6 rpm.	(Sharma & Ghoshal, 2020)
Green synthesis	silver nanoparticles using aqueous *Pisum sativum L.* (pea) pod extract	Antimicrobial activity	1 g of pod powder250 mL Erlenmeyer flask containing 100 mL double distilled water, boiled for 10 min, stored at 4 °C	(Alarjani, Huessien, Rasheed, & Kalaiyarasi, 2022)
	copper oxide (CuO) NPs	Antibacterial activity	pH 10, oven at 60 °C for 24 h,300 rpm for 4 min	(Fazal, Ara, Ishaq, & Sughra, 2022)
Packaging	CNCs from pea hull	The CMC/CNC composite films showed improved UV barrier, mechanical strength, water vapor barrier and thermal stability	CNC: 4% (*w/v*) NaOH solution at 75 °C for 4 h CMC: 45 °C for 8 h	(Li, Shi, He, Fei, & Peng, 2020)
	PHF- derived nanowhisker(PHFNW-t) and pea starch (PS)	Bionanocomposite film exhibit higher ultraviolet absorption, transparency, tensile strength, elongation at break, and water-resistance	Suitable hydrolysis time, in this work, is 8 h, pea hull fiber (PHF, 30 g) was mixed with sulfuric acid solution (250 mL, 64 wt%) and stirred vigorously at 45 °C	(Chen, Liu, Chang, Cao, & Anderson, 2009)
Textile	Pectin lyase	Dye wool fiber	pH 5 and 5 min microwave	(Atalla, Gamal, & N. G., Awad, H. M., & Ali, N. F., 2019)
Other	Pea peel	Inhibition of mild steel corrosion	1 to 4 M HCl at RTP temperatures (29.85–59.85 °C) in 1 M HCl	(Srivastava et al., 2018)

(2022) removed chromium from aquatic environments by using activated carbon derived from pea pods and found maximum adsorption capacity was 480.05 mg/g at an initial Cr (VI) concentration of 400 mg/L. Dod et al. (2012) carbonized GPP in an inert atmosphere to cause devolatilization and produce a porous carbon structure with a larger surface area. The material is then given a 24-h H_2SO_4 impregnation to increase the size of the carbon structure's pores even more. The carbonized GPP material, with particle sizes ranging from 75 to 300 μm, had shown exceptional MB dye adsorption capacities. The study found that an ideal pH of 7 and particle size of about 75 μm showed 96% of MB elimination. Additionally, it was shown that particle size had an impact on the adsorption process (Prajapati & Mondal, 2020). Carbonization and acid activation of pea pods made activated carbon with well-developed micropores and predominately acidic surface that contributes to it superior adsorption capabilities (Bello et al., 2017).

An alternative method for MB absorption involves the utilization of nanocomposite hydrogels (Malatji et al., 2021). Hydrogel nanocomposites remove dyes from wastewaters through a process called adsorption, where the pollutants in the wastewater are attracted and bound to the surface of the hydrogel. This is due to the hydrogel's three-dimensional polymeric network, which contains hydrophilic groups that can adsorb a large amount of water and pollutants. Polymer and polymer-based nanocomposite adsorbents have been emerging and promising materials for the removal of various pollutants from contaminated waters, in terms of strong mechanical strength, excellent hydraulics performance, high stability, and tunable surface chemistry (Pan et al., 2019). Polymers derived from plant and animal sources are of great interest in wastewater remediation due to their cost-effectiveness and renewable adsorption capabilities, one such polymer is nanocellulose (NC). NC has gained a lot of attention in various research fields due to its abundance in nature, nano-dimension, high surface area, stability and bio-compatibility (Tshikovhi, Mishra, & Mishra, 2020). Al-Gorair et al. (2022) recently used acid hydrolysis to produce cellulose nanocrystals (CNCs) from pea peels in their project. These CNCs were then incorporated into a nanocomposite hydrogel comprising pectin and acrylic acid (AAc) via irradiation and constructed Pectin-PAAc/CNC nanocomposite. The swelling and adsorption capacities of the resultant nanocomposite hydrogel were found to be improved by the addition of CNCs to the polymeric matrix. This novel nanocomposite hydrogel exhibited remarkable efficacy in removing MB dye from wastewater. Notably, an increase in the amount of MB dye in the wastewater had a favorable impact on the adsorption procedure by enabling more interaction between MB dye molecules and active sites on the nanocomposite surface. Increased dye concentration increased the driving force, which effectively reduced the mass transfer barrier that ordinarily separates the solute from the adsorbent surface. As a result, dye molecules moved quickly to open adsorbent sites at lower MB dye concentrations. However, as MB dye concentration increased, these active sites became progressively occupied. Moreover, it was observed that temperature exerted a substantial impact on the adsorption process. The elevated temperature not only accelerated MB dye adsorption onto the nanocomposite hydrogel but also indicated the occurrence of an endothermic reaction (Al-Gorair et al., 2022).

Biochar has significant potential in the remediation of pollutants from wastewater due to its unique physicochemical properties, including enriched surface functional groups (such as C − O, C═O, COOH, and OH), a high specific surface area, pore structures, and cationic exchange capacity, all of which are beneficial for carbon sequestration (Atukunda, Ibrahim, Fujii, Ookawara, & Nasr, 2022). Biochars remove contaminants from wastewaters through various mechanisms such as precipitation, surface complexation, ion exchange, pore filling, and electrostatic interactions. These mechanisms depend on factors like the physicochemical properties of the biochar, dosage, pyrolysis temperature, and the pH of the medium or effluent. Biochar's ability to adsorb pollutants in aquatic systems involves transferring pollutants from the liquid phase to the adsorbent surface, although the pollutants are not completely removed from the environment, potentially leading to the accumulation of contaminant residues in the biochar itself. Sorption capacity of the biochar was based on pore filling, electrostatic attraction, precipitation, complexation and ion exchange mechanism (Praveen, Jegan, Bhagavathi Pushpa, Gokulan, & Bulgariu, 2022). Biochar from biomass pyrolysis are more porous and carbon rich material has potential to be used as an integrated adsorptive material (Dong et al., 2023). Rubangakene et al. (2023) developed green pea peel biochar by using ferrous/ferric co-precipitation synthesis method and then used as an adsorbent. As a result of its paramagnetic characteristics, nano-ferromagnetic green pea biochar (NFGPBC) demonstrated good cycle performance, with a scant 8.9% decrease in capacity.

El-Nemr, Abdelmonem, Ismail, Ragab, and El Nemr (2020) investigated the efficacy of both unmodified and modified biochar derived from pea peel waste (PPW) biomass as an adsorbent for copper (II) removal from aqueous solutions through batch adsorption experiments conducted at room temperature. They first produced the biochar from the pea pods, and then they altered it with sulfuric acid, ozone, and ammonium hydroxide to add amino groups to the surface to improve copper removal from water. They discovered that the copper (II) adsorption capacities of unmodified biochar (referred to as Pea—B) and modified biochar (referred to as Pea-BO-NH_2), with removal efficiencies of 100% and 79%, respectively, showed considerable copper (II) adsorption capacities. In a related study, El-Nemr, Abdelmonem, Ismail, Ragab, and Nemr (2020) used biochar (unmodified-Pea-B) grafted with ammonium hydroxide and Tetraethylene tetramine (TETA), as well as two amine-functionalized biochars, Pea-BO-NH_2 and Pea-BO-TETA, to evaluate their efficacy in eliminating the azo dye i.e. Acid Orange 7 (commonly written as AO7). With Pea-BO-NH_2 displaying a 99% removal rate, Pea-BO-TETA getting a 98% removal rate, and Pea-B biochar producing a 96% removal rate. The inclusion of amine groups on the biochar surface increased its ability to absorb dyes from water, making the modified biochar's effective adsorbents for the removal of such colors. Modified biochar found efficient adsorbents for the removal of such dyes as amine groups on the surface of biochar increase their ability to absorb dyes from water (El-Nemr, Abdelmonem, Ismail, Ragab, & Nemr, 2020). In another study, El-Nemr et al. (2022) prepared Biochar with sulfur groups (Biochar-SO) by using sulfuric acid and tested its efficiency in eradicating chromium (Cr^{6+}) ions. When using Biochar-SO, they found that the maximum rate of Cr^{6+} ion removal was 90.74%.

Activated carbon derived from waste biomass is a desirable material due to its non-toxic nature, insolubility in water, and excellent resistance to oxidizing and reducing agents (Chaudhry, Zaidi, & Siddiqui, 2017). Due to its magnetic properties, which allow for effective separation using external magnetic fields, magnetic-activated carbon has also demonstrated promise in the remediation of arsenic (As) pollution (Rahman, Erdem, Sahin, & Erdem, 2020). A recent study by Sahu et al. (2022) utilized PPW to synthesize magnetic-activated carbons, denoted as MPAC-500 and MPAC-600 (magnetic-activated carbons synthesized from the peel of peas pyrolyzed at 500 °C and 600 °C temperatures, respectively). These substances were employed to remove As (III) and As (V) ions from water. Due to its lower carbon content (43.19%) and greater iron concentration (8.01%) compared to MPAC-500 which had a higher carbon content (71.75%) and a lower iron level (1.49%), MPAC-600 showed superior adsorption effectiveness. Furthermore, Swain et al. (2019) employed zirconium-impregnated carbon-rich PPW, obtained using zirconium oxychloride ($ZrOCl_2{\cdot}8H_2O$) solution and ground PPW, as an engineered biochar substance for the removal of fluoride from aqueous solutions. Remarkably, this material successfully absorbed 95% to 98% of the fluoride at a high adsorption rate.

The optimization of pH is a critical factor in achieving the effective removal of chromium (VI) when utilizing agro and horticultural waste as a biosorbent. It has been determined that a pH range between 2.0 and 3.0 showed the best results for this purpose. Industries such as tanneries, electroplating, and metal finishing, which discharge chromium (VI) in their wastewater into natural streams, can significantly mitigate this pollution by employing a cost-effective biosorbent. These sectors benefit financially from the cost-effective removal of chromium (VI), which lowers the overall cost of the production process and the final product (Sharma & Ayub, 2019). Furthermore, it should be noted that the efficiency of reactive blue dye (RB19) removal is also influenced by pH. Particularly, a decrease in pH enhances the removal efficiency. This phenomenon is attributed to the degree of ionization on the surface of the adsorbent and its interactions with the adsorbate, which are of great importance. The adsorption process of RB19 demonstrates a favorable trend under acidic conditions, primarily due to electrostatic attractions between the negatively charged functional groups of the anionic dye and the positively charged surface of the adsorbent. Consequently, it can be deduced that the removal of RB19 is chiefly governed by the pH level and the quantity of the adsorbent utilized. Notably, a pH of 2 and a temperature of 35 °C showed the highest removal rate of 99.42% (Demirhan, 2020).

2.2. Development of nutritious food products

The excessive exploitation of natural resources, worsened by the increasing global population, is a major factor contributing to the depletion of our planet's vital resources. An effective solution to this difficulty can be found in the optimal usage of by-products, residues, and waste materials that come from agro-industrial and food processing activities. Notably, significant amounts of legume residues, particularly those derived from peas, are produced annually. These remnants constitute a significant reservoir of plant based proteins, playing a crucial role in fulfilling the increasing global need for protein (Tassoni et al., 2020). Utilizing pea peels in powder form (after cleaning, drying and grinding) as a value-added component and their incorporation to various food recipes for the production of wholesome snack crackers and dehydrated soup can optimize protein consumption. Mousa et al. (2021) produced a dehydrated version of green curd made from pea peel that has a significant protein concentration of 35%. The produced crackers showed elevated quantities of important minerals and amino acids. The soup samples showed greater mineral content, particularly in terms of calcium (Ca), magnesium (Mg), iron (Fe), and zinc (Zn). In a study, Hanan et al. (2020) formulated instant pea soup powder showing a notable increase in dietary fiber content, reaching 13.25%. The formulated soup exhibited reduced carbohydrate levels and higher proportions of both protein and fat. This highlights the opportunity to use pea peel in a variety of food applications to improve their nutritional content. Similar to this, Pooja et al. (2022) added pea peel powder to muffins to enhance their nutritional value. The outcome was a noteworthy 13.78% dietary fiber level and 8.94% protein content. Furthermore, in the context of nutritional enhancement, it was found that incorporating pea pod powder (PPP) into eggless, low-fat mayonnaise could enhance its nutritional value by introducing dietary fiber and micronutrients. PPP was added as protein-polysaccharide particles, which improved the sensory properties along with balancing the rheological and textural parameters. This improved emulsion stability is shown by a greater activation energy and heat stability index (Rudra et al., 2020). Additionally, when PPP was added to buckwheat bread at different concentrations of 10, 15, and 20%, out of this 15% show the nutritional quality of the bread improved, with an increase in dietary fiber (12.1%), pigments (26.8%), and protein content (13.05%) and a decrease in carbs by 33.6% (Hanan et al., 2021). Rudra et al. (2020) reported that pea pod possesses good content of dietary fiber (32.83%). Fendri et al. (2016) reported that it is a source of dietary fiber (43–58%), protein (11–13%), micronutrients (iron: 1.2 mg/100 g, copper: 0.05–1.09 mg/100 g, zinc: 0.16–0.92 mg/100 g). The naturally present combination of soluble and insoluble fibers in pea peel has a synergistic effect, resulting in an enhanced texture of the bread crumb (Hanan et al., 2021).

2.3. Nutraceuticals

Nutraceuticals are medicinal foods that play a role in enhancing health, maintaining wellbeing, improving immunity, and thereby preventing as well as treating specific diseases. Bioactive compounds from food waste can be extracted and utilized for the development of nutraceuticals and functional foods (Kumar, Yadav, Kumar, Vyas, & Dhaliwal, 2017). Fruit and vegetable processing waste is rich in organic matter, phytochemicals, and compounds with nutraceutical properties (Sharma et al., 2016). For instance, the pea pod extract has been found to contain significant amounts of various polyphenols, including 5-caffeoylquinic acid, epicatechin, and hesperidin (Castaldo et al., 2022). These polyphenols are regarded as valuable natural sources of antioxidants and useful chemicals, as highlighted by Fendri et al. (2022). Pea peels have also attracted attention due to their nutritive and therapeutic properties. The ethanolic extract of pea peels e has highest number of polyphenols and flavonoids, 165.43 mg GAE/g and 26.63 mg QE/g, respectively as revealed by a previous investigation (Taher, 2019). Hesperidin was documented as the most abundant polyphenol (2017.2 μg/g) imparting pea peel extract an antioxidant property. The ethyl acetate fraction had the lowest IC_{50} values for DPPH, NO and H_2O_2 assays with the values of 167.23, 302.36 and 317.66 μg/mL, respectively. A significant and negative correlation was remarked between total flavonoids content and IC_{50} for the scavenging DPPH radical (Taher, 2019). Gelatin capsules known as NARC (non-acid-resistant capsules) and hydroxypropyl methylcellulose capsules known as ARC (acid-resistant capsules), both meeting pharmaceutical standards, were developed from pea pods in the context of pharmaceutical formulation to encapsulate 0.500 g of a polyphenolic extract. Total phenolic content (TPC) measurements at different stages of an in vitro gastrointestinal digestion simulation showed that ARC capsules had significantly higher TPC values (5.47 mg) during the duodenum and colonic stages than NARC capsules (3.73 mg). This finding implies that, when compared to NARC samples, ARC samples display a greater antioxidant capacity during simulated GI digestion. It is also important to note that the use of the “active targeting release concept” has considerable potential as a powerful method for the exact delivery of bioactive compounds to particular tissues (Castaldo et al., 2022). Ouis &Hariri, (2023) obtained pea pod essential oil by the addition of 2 l of water at 80–85 °C to 800 g of pea pod for 2 h having antioxidant property and has an effective inhibiting lipid peroxidation. Pea peel polysaccharides (PPP) presented higher antibacterial capacity, it is proposed that the polysaccharide disrupted the cell wall and cytoplasmic membrane, leading to the dissolution of the protein and leakage of essential molecules, resulting in cell death (Belghith-fendri et al., 2018). The main monosaccharides of polysaccharides in different purified levels were rhamnose, arabinose, galactose, glucose, and mannose (Zhang et al., 2020). Hadrich et al. (2014) conducted research to explore the antimicrobial properties of extracts derived from pea peel against a range of bacterial strains, including *Staphylococcus aureus* (ATCC 25923), *Escherichia coli* (ATCC 25922), *Pseudomonas aeruginosa* (ATCC 27853), and *Salmonella enterica* (ATCC 13883). Additionally, they assessed the antifungal characteristics of these extracts against *A. niger* and *Candida albicans*. This experiment established the foundation for regarding pea peel extracts as a prospective element of conventional medicine.

The antibacterial activities of pea peels, orange peels, and rice husks are also attributed to their intrinsic phytochemical compositions. The antimicrobial efficacy of extracts derived from agricultural waste was assessed against 4 strains of Gram-negative bacteria, namely *Pseudomonas fluorescens*, *Salmonella choleraesuis*, *Enterobacter aerogenes*, and *Proteus* spp. The findings demonstrated that all of the extracts had inhibitory effects on the bacterial strains listed. The pea peel extract and orange peel extract both demonstrated better inhibitory responses against *H. capsulatum* and *A. niger*, respectively, among the samples examined. A moderate amount of inhibition was also seen by the rice husk extract against both fungal strains. According to these studies, the antibacterial capabilities of extracts obtained from agricultural waste make them potentially useful in the food and pharmaceutical industries (Naqvi et al., 2021). Pea peel extract demonstrated inhibition against *Pseudomonas fluorescens,* and antifungal efficacy was also observed against two distinct fungal strains, namely *A. niger and H. capsulatum*. The extract under investigation was found to contain polyphenolic compounds, predominantly consisting of flavonoid glycosides, namely quercetin, kaempferol, and apigenin, as well as various phenolic compounds (Abdelghffar et al., 2021).

The pea pods exhibit a significant protective effect against cardiac toxicity caused by doxorubicin (DOX- an antibiotic derived from the *Streptomyces peucetius* bacterium). Pea peel extract exhibited protective potential against oxidative myocardial injury induced by DOX (Abdelghffar et al., 2021). The administration of DOX increases the levels of various serum biomarkers associated with myocardial dysfunction such as ALT, LDH, CPK, and CK-MB. Additionally, there was an elevation in lipid profile and proinflammatory cytokines. Reduction in cardiac levels of antioxidants such as GSH, SOD, GPX, and CAT were observed (El-Motelp, 2023). In addition, it was observed that the gene expressions of Bcl-2 (an anti-apoptotic gene) were down-regulated, while the gene expressions of Bax (a pro-apoptotic gene) were upregulated (Emi, Kim, Tanabe, Uchida, & Toge, 2005). The therapeutic qualities of pea peel extracts depend on a blend of chemicals with both high and low molecular weights. Their biological potential was enhanced by chemically sulfating aqueous preparations. In a study, a comparative analysis of aqueous extracts and their sulfated derivatives with established anticoagulants like Heparin and Hemoclar was carried out focusing on their anticoagulation and fibrinolysis properties. Notably, the aqueous extracts had a far faster response than the traditional anticoagulant Heparin, which suggests their potential as rapid-acting anticoagulants. Heparin normally takes 90 min to commence clot formation. According to the research, sulfated extracts that are insoluble, neutral, and alkaline also have anticoagulant effects. Furthermore, the research found that when compared to the well-known chemotherapeutic drug DOX, sulfated acidic insoluble, neutral soluble, and alkaline soluble extracts showed powerful activity against MCF-7 cancer cell lines. These findings emphasized the potential of pea peel extracts as prospective therapeutic agents in both the anticoagulation and cancer treatment fields, supporting their long-standing use in folk medicine (Abd El-Galil et al., 2021).

Mejri et al. (2020) administrated orally pea pod methanol extract (PPE) to diabetic mice showed decreased in serum glucose levels, alanine aminotransferase, aspartate aminotransferase, urea, creatinine, alkaline phosphatase and lactate dehydrogenase activities. It reduced lipid peroxidation, and H_2O_2 and SH contents, but it significantly ($p < 0.05$) increased the activities of antioxidant enzymes (CAT, GPX and SOD) in the liver, kidney and testis. Moreover, PPE effectively reduced serum triglycerides, cholesterol and LDL and restored the hepatic, renal and testicular fatty acid profiles suggesting its promising anti-hyperlipidemic effect. Overall, PPE could be useful to help manage diabetes and its associated hyperlipidema, to reduce the risk of oxidative stress and to decrease liver, kidney damage. One of the therapeutic styles for alleviating type 2 diabetes mellitus (T2DM) is to suppress intestinal glucose absorption through the quench of carbohydrate hydrolyzing enzymes such as α-glucosidase and α-amylase. Natural α-amylase inhibitors represent an interesting route to the management of post-prandial hyperglycemia by declining glucose release from starch. Butanol fraction of pea peel showed considerable anti-αamylase activity (IC_{50} = 1.61 mg/mL) (Taher, 2019). Elderly persons may benefit from consuming fiber-enriched meals to help them fulfill their recommended daily fiber intake. However, some components with high fiber content may not have a substantial effect on bowel movements and may potentially lead to undesirable gastrointestinal symptoms. Pea hull fiber (PHF) fortified snacks may not exert a substantial effect on suppressing hunger. Nevertheless, PHF may potentially function as a suitable dietary fiber option for elderly individuals who face the possibility of malnutrition (Alyousif et al., 2020).

2.4. Biofuels

N-butanol is a promising renewable biofuel for utilization in internal combustion engines. Its fuel characteristics indicate that it may surpass low-carbon alcohols or biodiesel in terms of performance (Han, Yang, Wang, Tjong, & Zheng, 2017). Biobutanol exhibits fuel characteristics that closely resemble those of petrol, rendering it a highly promising biofuel (Liu et al., 2022). The production of sustainable biobased butanol is achieved through the ABE pathway utilizing *Clostridium* spp. during the process of fermentation (Vamsi Krishna, Bharathi, George Shiju, Alagesan Paari, & Malaviya, 2022). The optimal agricultural residues for ABE synthesis exhibit elevated levels of cellulose and hemicellulose while possessing reduced amounts of lignin (Liu et al., 2022). The utilization of pea pod residue as a carbon source in the production of bio-butanol is a promising avenue, owing to its substantial holocellulose composition. Specifically, the dry weight percentages of cellulose and hemicellulose in pea pod waste are 32.08% and 21.12%, respectively (Nimbalkar et al., 2018). For the formation of butanol, detoxification is carried out on the dried pea waste sample before fermentation to eliminate any inhibitory chemicals that may have been produced during pretreatment. The sample is saccharified as shown in Fig. 1(a) using a dilute acid catalyst. ABE-I was obtained as an outcome (Nimbalkar et al., 2018). In comparison to ethanol, butanol exhibits superior energy density and is not susceptible to separation in the presence of water. Nonetheless, it is worth noting that its chemical yield is comparatively lower than that of ethanol (Rathour, Ahuja, Bhatia, &

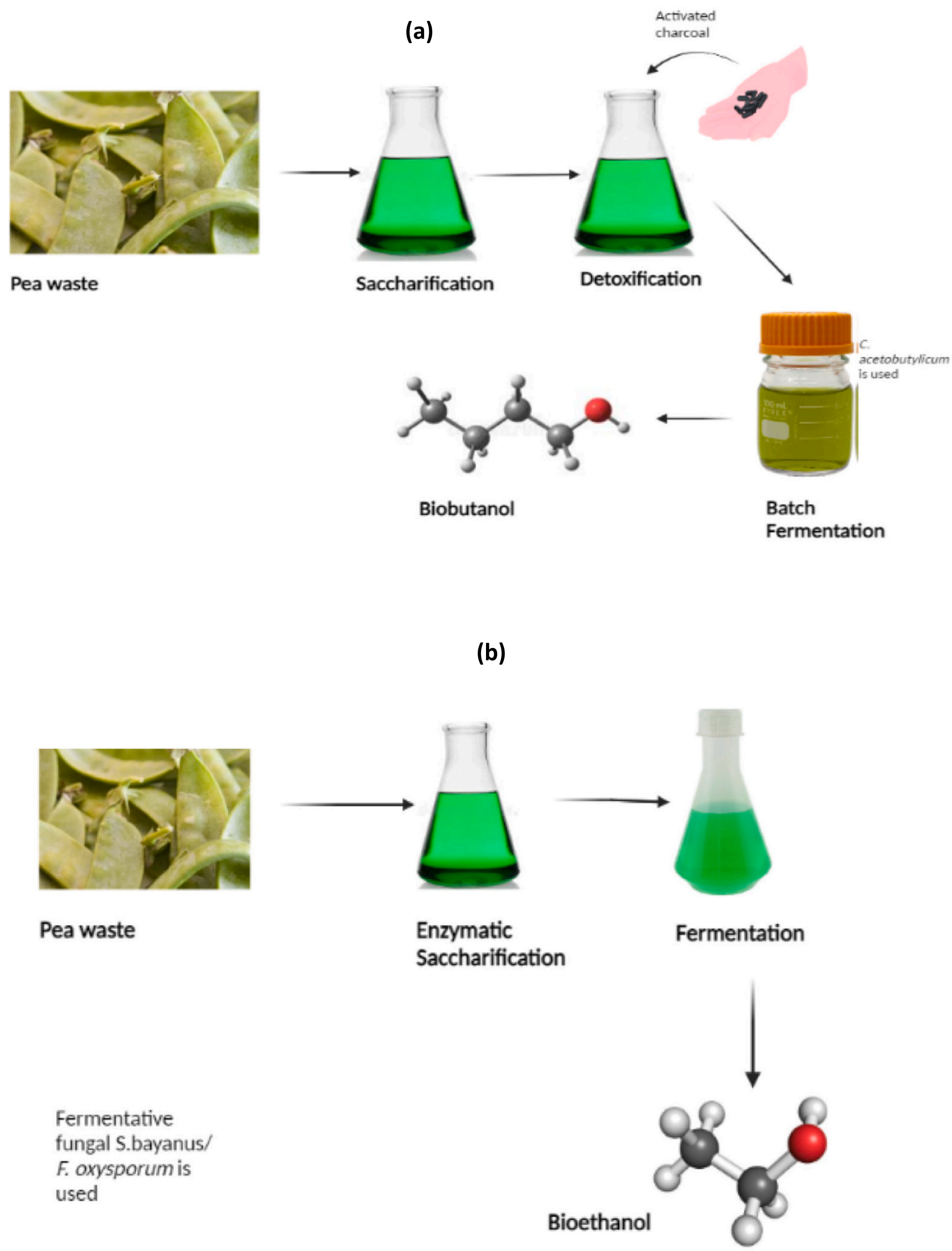

Fig. 1. Production of biofuels (a) showing production of biobutanol (b) showing production of bioethanol using pea pod.

Bhatt, 2018).

In addition, pre-treated pea waste has the potential to be utilized for large-scale bioethanol production through the implementation of fermentative *S. bayanus* and *F. oxysporum*. The production steps for this process are illustrated in the Fig. 1(b) (Rehman, Gulfraz, Raja, Haq and Anwar, 2015). Furfural is a prominent chemical compound that is utilized extensively in various industries such as oil refining, plastics, pharmaceuticals, and agrochemicals. It is one of the many compounds derived from lignocellulosic materials (Jaswal, Singh, & Mondal, 2022). In a study conducted by Yadav et al. (2017), a notably higher furfural yield of 5.27 g/L was achieved when utilizing pea pods. This was accomplished by employing a 6% H_3PO_4 concentration and a liquid-to-solid ratio of 1:10 at a temperature of 160 °C. The yield of furfural was notably impacted by key reaction parameters, including acid concentration, reaction temperature, and the ratio of liquid to solid components (Adebayo, Ogunjobi, Oluwasina, & Lajide, 2023). The production of biofuels by utilizing pea pods are elaborated in Fig. 1.

2.5. Biocolorants

Biocolors can be produced from agro byproducts using microorganisms, particularly yeasts and bacteria, which can convert various types of organic matter into pigments. Bio-colorants are preferable to synthetic colors because they impart a specific color to food, textile, pharmaceutical, and cosmeceutical items but their use in the food industry is most preferred these days because they contain bio-active antioxidant nutrients that are regarded as safe for eating. The production of biocolors by utilizing natural food waste materials is not well commercialized yet but researches have been performed on lab-scale and efforts have been done to produce natural bio-colors on commercial scale (Thakur & Modi, 2022). Agro-industrial waste materials, specifically pea pods onion peels, potato skins, and mung bean husks, are utilized as substrates for carotenoid production from *Rhodotorula mucilaginosa*. Onion peels and potato skin were employed as carbon sources due to their elevated sugar concentration, while mung bean husk and pea pods were utilized as nitrogen sources owing to their high nitrogen concentration. The objective was to produce carotenoids from the yeast strain *Rhodotorula mucilaginosa*. The fermentation process was conducted at pH of 6.1, temperature of 25.8 °C, and an agitation rate of 119.6 rpm. The application of liquid chromatography-mass spectrometry (LC-MS) for the analysis of extracted pigment has verified the existence of additional carotenoids in conjunction with β-carotene. The predominant carotenoids identified were torularhodin, β-carotene, and torulene (Sharma & Ghoshal, 2020). The biocolors produced by employing microbes represent coloring agents obtained from biological sources, including biomass and agricultural residues, through the metabolic activities of microorganisms. The production of biocolors through microbial processes offers several advantages, including their nontoxic nature, superior quality, biodegradability, environmental compatibility, and independence from seasonal fluctuations. Consequently, the biotechnological synthesis of natural colors using cost-effective substrates like agro-industrial residues emerges as an economically viable and environmentally friendly approach for natural color production (Kaur et al., 2022). The health benefits of using natural colors in processed foods are described in Fig. 2.

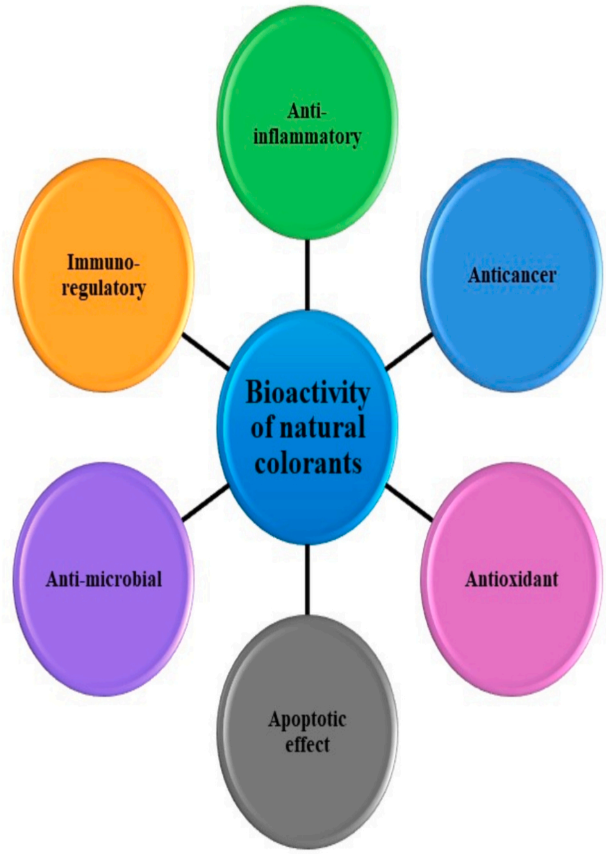

Fig. 2. Health benefits of using natural colors in processed foods.

2.6. Extraction of low methoxylated pectin (LMP)

The production of LMP involves a series of steps that utilize fruit byproducts as the primary source material and is derived from high methoxylated pectin (Duan et al., 2022). For extraction of LMP from pea hulls (PH), citric acid and nitric acid were employed as the extraction media. The results indicate that citric acid produced greater amounts of pectic polysaccharides (PPS) (ranging from 3.5% to 9.8%) in comparison to nitric acid (ranging from 1.4% to 8.0%). A discrepancy of objectives arose between achieving a high yield and maintaining the purity of the extracted PPS. The findings of the composition analysis indicate that PPS when subjected to extraction conditions that are considered 'mild' (at a pH of 2 and a temperature of 70 °C), comprise homogalacturonan, xylo-galacturonan, and rhamnogalacturonan, which are accompanied by galactose and arabinose side chains (RG-I). The maximum yield is achieved at elevated temperatures (90 °C) owing to the enhanced solubilization of cell wall polysaccharides. Under conditions characterized as "harsh" (pH 1, 90 °C), the purity of PPS is enhanced through a comparatively elevated concentration of uronic acids, but low yield is obtained. The observed phenomenon is ascribed to the cleavage of non-galacturonic acid constituents and the continuous depolymerization of the galacturonic acid-rich pectin. The PPS obtained exhibits a low level of acetylation, measuring at 4%, and a relatively elevated protein concentration of 7% (Gutöhrlein, Drusch, & Schalow, 2020).

LMP has been found to have various health benefits. Muñoz-Almagro et al. (2021) demonstrated its lipid-lowering effects, reducing cholesterol and triglyceride levels and also highlighted its potential in development of low-glycemic food formulations, which can aid in the prevention and treatment of diabetes. Tang et al. (2023) further supported this, showing that LMP can prevent gut epithelial cell barrier disruption and reduce the expression of the sodium-glucose co-transporter, which is involved in glucose transport. They emphasized the stability of LMP in aqueous solutions. These studies collectively suggest that LMP can be beneficial for lipid management and gut health.

2.7. Rheological modification of oil

In this scientific investigation, two distinct coarse fractions were derived from yellow peas: pea hull (PH) and the epidermal cell wall (PCW). These fractions were studied as potential rheological modifiers for an oil phase. As the particle volume fraction (φ) within the PH and PCW-in-oil suspension was increased, a significant transition had been observed. That transition occurred at approximately φ = 0.20 and marked a shift from a Newtonian fluid to a viscoelastic substance. It was characterized by the emergence of elasticity and a noticeable shear-thinning behavior. In the analysis, a refractive index of 1.54 was assumed for the particles, and the absorption index of 0.1. At higher volume fractions (φ ≈ 0.50), both the PH and PCW-in-oil dispersions exhibited rheological properties resembling those of solids and displayed a paste-like appearance (Calabrese et al., 2021). The adoption of vegetable oil and pea fibers for the production of solid matrices with a substantial oil content, maintained at around 20 °C is a promising strategy to replace saturated fats in a range of food products, such as spreads and laminated pastries (Calabrese et al., 2021). A significant interest has been shown in oleogels and emulsion gels as prospective alternatives for saturated fats in a variety of food applications. Oleogels are solid-like structures formed by incorporating biopolymers such as dietary fibers and proteins, they offer solid fat texture and rich unsaturated fatty acids. They serve as fat substitutes, providing solid texture and a healthy profile (Guo, Cui, & Meng, 2023). The addition of pea pod dietary fiber (PPDF) to low fat goat meat butter showed a decrease in cooking losses (15%) and 5% of shrinkage (5%) (Kumar, Kumar, Vishwakarma, & Kumar Singh, 2021).

2.8. Synthesis of nanoparticles (NPs) as valuable products

Silver nanoparticles (AgNPs) were synthesized using the pea pods as a green source, whereby a 1 mM silver nitrate solution was used as the initial reactant. A quantity of approximately 1 g of pea waste powder was homogeneously blended with 100 mL of double distilled water in a 250-mL Erlenmeyer flask. The aqueous extract of pea pod was utilized for the green synthesis of AgNPs. A solution of 1 mM silver nitrate was prepared and placed in an Erlenmeyer flask with a volume of 100 mL. The phenomenon of color alteration was observed concomitantly with the synthesis of AgNPs. After a 2-h incubation period, the solution underwent a color change to a dark brown hue. The chromatic intensity was enhanced to a greater extent and no alteration in hue was detected after a 4-h duration of treatment. The AgNPs that were synthesized exhibited an approximate size of 30 nm. The following human intestinal pathogens were utilized in the study: *Pseudomonas aeruginosa* ATCC27853, *E. coli* ATCC 25922, *Enterococcus faecalis* 700,802, *Streptococcus gordonii* ATCC 49818, Methicillin-resistant *Staphylococcus aureus* (MRSA) ATCC 4330, and *Staphylococcus aureus* ATCC 25923. The antimicrobial efficacy of AgNPs was found to be significantly higher against *S. aureus* ATCC25923 (22 ± 2 mm) in comparison to other bacterial strains. AgNPs are strongly influenced by their shape, size, concentration, and colloidal state. AgNPs interacts with bacteria, fungi and viruses in a shape-dependent manner. Alterations in the cell membrane of the gram-negative *E. coli* bacterium upon treatment with differently shaped AgNPs was observed both in liquid and semi-solid agar medium. Shape of the nanoparticles is one of the properties, which affects other physico-chemical properties of the nanoparticles (Raza et al., 2016). The antibacterial effect of AgNPs as proposed is due to their smaller particles size that apparently has superior penetration ability into bacteria, especially in Gram-negative (Dakal et al., 2016). Ionic nanopariculate metal oxides are among the potentially interesting antimicrobial agents, because of their extremely high surface areas and having unusual crystalline structures with high number of edges and corners and other reactive sites, these nanoparticles have high surface areas and unusual crystalline structures to give CuO-NPs with antimicrobial activity that is dose dependent (Amiri et al., 2017).

Alarjani et al. (2022) reported that the zone of inhibition ranged from 15 to 22 mm, indicating variability in antibacterial activity. The greener method for synthesizing NPs is becoming increasingly significant owing to its simplicity and cost-effectiveness. The production of NPs utilizing vegetable peels is entirely environmentally friendly. The implementation of an environmentally conscious methodology involves conducting synthesis in an aqueous solution, utilizing a minimal quantity of chemicals, and employing a low fabrication temperature. The utilization of $CuCl_2.2H_2O$ resulted in the production of NPs with particle sizes of 47.2 nm, 32.5 nm, and 40.7 nm, derived from pea peels, cauliflower, and potatoes, respectively. The study determined the inhibitory effect of CuO-NPs at a concentration of 45 μg/mL on various bacterial strains, with the order of susceptibility being *Pseudomonas aeruginosa* > *Escherichia coli* > *Bacillus subtilis* > *Staphylococcus aureus*. The biocidal effect of NPs was observed to be more pronounced on the growth of Gram-negative bacteria as compared to Gram-positive bacteria. NPs exhibit greater efficacy in inhibiting and inactivating cellular growth compared to their parent materials when compared to the control (Fazal et al., 2022).

2.9. Packaging

The food industry uses films and other forms of packaging to store food. Food packaging is evolving in response to changing consumer demands for preserved, fresh and tasty food, as well as convenient packaging that also assists in quality control and extends shelf life. In addition to these factors, there is an advance in materials science and technology and a reduction in the use of non-biodegradable materials in the production of packaging (Azevedo et al., 2020). Upasana et al. (2019) provides a broader perspective, discussing the use of food wastes, including pea waste, in the production of organic-based packaging materials. These studies collectively suggest that pea waste has the potential to be a valuable resource in the development of sustainable packaging solutions. Azevedo et al. (2020) highlight the use of protein-based materials, such as pea protein isolate, in the development of biodegradable containers and nanocomposite films for packaging.

In another research, investigated the chitosan (CH)-based gel films with varying concentrations of empty green pea pod extract (EPPE) for potential food packaging applications. The addition of EPPE increased film thickness, density, and opacity while decreasing water vapor permeability, water solubility, oil absorption, and whiteness index. EPPE films exhibited improved tensile strength, elongation, biodegradability, and antimicrobial properties compared to pure CH films. Scanning electron microscopy (SEM) analysis showed agglomerates formation with increasing EPPE concentration. Additionally, packaging corn oil in CH-based EPPE films slowed the rise of thiobarbituric acid and peroxide values, suggesting potential industrial application in active food packaging (Elsebaie et al., 2023).

To reinforce carboxymethyl cellulose (CMC), which is characterized by its needle-like form, CNC isolated from PH was used. The CMC-based composite films had a CNC content that ranged from 0% to 10%. CNC achieved homogeneous dispersion inside the CMC matrix at a concentration of 5% weight, leading to the creation of homogenous films. These CMC/CNC composite films showed improved thermal stability, improved water vapor resistance, improved mechanical strength, and improved UV barrier characteristics. Notably, compared to pure CMC films, the composite film reinforced with 5 wt% CNC showed a 50.8% improvement in tensile strength and a 53.4% decrease in water vapor permeability. Thus, showing that application of the 5 wt% CNC-reinforced composite films as packaging material for red chilies yielded promising results. It mitigated weight loss and preserved the vitamin C content in the chilies, as compared to uncoated chilies. This suggests that CMC/CNC composite films hold significant potential as edible food packaging materials (Li et al., 2020). In another study, by using dispersions of PHF nanowhiskers (PHFNW-t), produced by hydrolyzing PHF with different sulfuric acid treatment times (t), bionanocomposite films were produced. The dimensions of the nanowhiskers were between 240 and 400 nm in length, 7 to 12 nm in diameter, and aspect ratios of length and diameter (L/D) between 32.22 and 36.00. These PHFNW-t nanowhiskers were used in conjunction with pea starch (PS) as ingredients in the production of nanocomposite films.

Comprehensive structural and performance analyses were conducted on the resulting PS/PHFNW-t nanocomposite films. In contrast to both plain PS films and PS/PHF films (control samples with $t = 0$ h), they significantly improved UV absorption, transparency, tensile strength, elongation at break, and water resistance. Particularly noteworthy was the remarkable improvement in transparency, tensile strength, and elongation at break in PS/PHFNW-t films, attributed to the high L/D ratio of PHFNW-8. These findings underscore the profound impact of hydrolysis time on the structural attributes (including length, diameter, and L/D ratio) of PHFNW-t nanowhiskers, as well as the subsequent influence on the structure and performance characteristics of PS/PHFNW-t nanocomposite films (Chen et al., 2009).

2.10. *Manufacturing of enzymes for the textile industry*

Biocatalysts like enzyme technology are potential biotechnology tools. *Penicillium expansum* RSW_SEP1, a red sea water fungus strain discovered by 18S rRNA gene (MH754656). Agricultural waste served as the main, affordable carbon source for the manufacturing of pectin lyase (Sharma, Rawat, Bhogal, & Oberoi, 2015). The function of pea waste products in producing enzymes involves utilizing these waste materials as cost-effective substrates for obtaining enzymes through fermentation techniques (Mateii et al., 2021). Pods of pea and sugar cane bagasse (SCB) mixed in a 5:5 (*w*/w) ratio, kept at pH 6, and injected with 8 mL of spore suspension were the ideal conditions for this process. The enzyme activity reached its peak under these circumstances at 88.83 U/mL. After 5 min of pretreatment at pH 5.0, microwave-dyed wool fibers containing green algae had the maximum color strength (K/S) at 15%. The microwave-dyed wool fibers containing green algae had the maximum color strength (K/S) at 15% after 5 min at pH 5.0. This work isolated and molecularly identified a marine fungus strain that produces pectin layers from agricultural wastes and dyed wool fibers (Atalla et al., 2019). Cellulase enzyme was also procured by *A. niger* by using PPW through solid state fermentation and resulted in filter paper cellulase (FP) and β-glucosidase (BGL) activity of 30 FPU/gds and 270 U/gds, respectively (Sharma et al., 2015).

Fig. 3**.** gives an overview of enzymes production from agro-waste based media.

2.11. *Inhibition of steel corrosion*

Food waste products can act as an organic inhibitor to inhibit the corrosion in steel. These organic inhibitors work by forming a protective layer on the metal surface, which prevents the metal from reacting with its environment. This method is considered more sustainable and environmentally friendly compared to traditional synthetic inhibitors, which can be toxic and harmful to the environment. Research has shown that these organic inhibitors can be effective in various acidic media and can significantly reduce the corrosion rate of steel. Aqueous extract derived from pea pods is a highly effective inhibitor for the corrosion of mild steel. Its inhibitive action entails covering the active corrosion spots on the mild steel's surface with a shield. As a result, in the presence of HCl solution, the exposed surface's electrochemical activity is dramatically diminished. Using weight loss, polarization curves, and electrochemical impedance spectroscopy (EIS), the exceptional inhibitory efficiencies of the extracts of pea pods were evaluated as 91%, 87%, and 90%, respectively. These excellent inhibitory efficiencies were attained in a 400 mg/L solution of 1 M HCl. The examination into mild steel's corrosion behavior in the presence of pea peel aqueous extract was carried out throughout a range of HCl concentrations from 1 M to 4 M, both at ambient room temperature and within the temperature range of 29.85 to 59.85 °C (Srivastava et al., 2018).

3. Conclusion

Pea pod waste, often considered an agricultural byproduct, has found several innovative applications that not only minimize waste but also offer significant benefits to diverse industries. Activated carbon derived from GPP has proven to be a cost-effective approach in the discipline of water treatment, effectively eliminating contaminants including metallic ions and dyes. The nutritional and therapeutic properties of various food products like crackers, instant soup powder, muffins, and mayonnaise are also improved by the incorporation of pea pod waste. The utilization of pea pod waste as a biofuel feedstock in sectors other than the food industry has the potential to contribute to the promotion of renewable energy. This method is also utilized to produce natural colorants, extraction of LMP for food applications, alteration of oils to develop healthier fats, synthesis of green NPs for antimicrobial purposes, and enhancement of food packaging materials. The versatility and value of pea pod waste are evident in its contributions to textile manufacture and in the inhibition of corrosion processes, among other eco-friendly and economically viable uses.

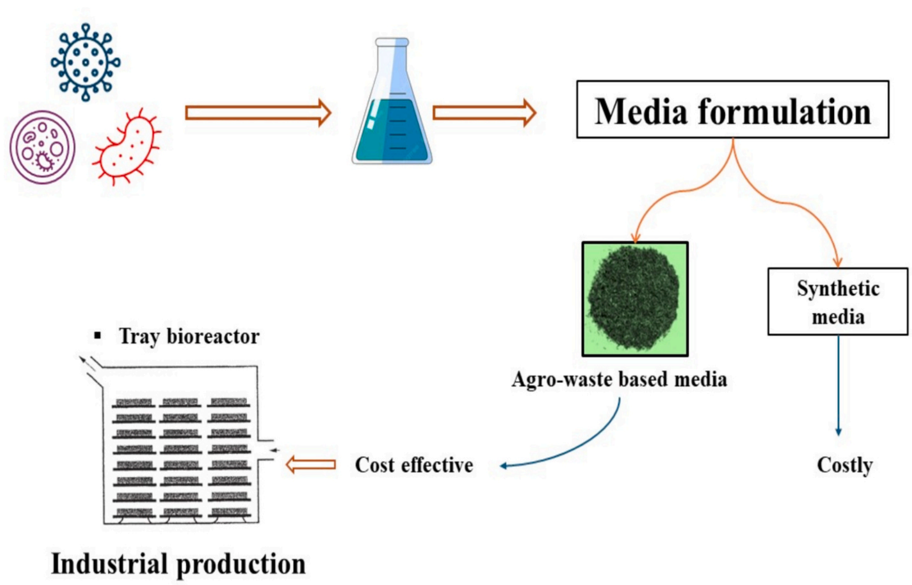

Fig. 3. An overview of enzymes production from agro-waste based media.

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CRediT authorship contribution statement

Rubab Fatima: Writing – review & editing, Methodology, Conceptualization. **Filza Fatima:** Writing – review & editing, Methodology, Conceptualization. **Ammar B. Altemimi:** Writing – review & editing, Visualization, Software. **Nadia Bashir:** Writing – review & editing, Investigation, Formal analysis. **Hassan Mehmood Sipra:** Writing – review & editing, Formal analysis, Data curation. **Syed Ali Hassan:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Waqar Mujahid:** Writing – review & editing, Visualization, Software. **Aamir Shehzad:** Writing – review & editing, Data curation. **Gholamreza Abdi:** Conceptualization, Data Curation, Methodology, Writing – review & editing, Supervision. **Rana Muhammad Aadil:** Conceptualization, Data Curation, Methodology, Writing – review & editing, Supervision.

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.

Data availability statement.

The data will be available upon request.

Data availability

No data was used for the research described in the article.

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