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Eco-innovation in action: valorizing vegetable waste into high-value ingredients for sustainable applications

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Circular economy concepts are inspiring the global community by creating new business opportunities that transform waste into wealth and energy. Processing industries generate significant quantities of vegetable waste (VW) in the form of peels, seeds, and pomace. Improper disposal of this waste poses significant challenges to the environment, ecology, economy, and food security. However, these by-products are rich in valuable biomolecules. In recent years, research has increasingly focused on converting these low-value agricultural residues into high-value functional ingredients. These biomolecules can be extracted and utilized in various applications, including food, feed, nutraceuticals, dietary supplements, and energy. While most previous work has focused on food waste from a holistic perspective, studies on VW valorization are relatively limited, primarily concentrating on biomass conversion and the extraction of bioactive compounds. However, several niche areas remain unexplored due to a lack of research in the global arena. This review explores the most promising methods for valorizing VW across both food and non-food sectors while also addressing the challenges in implementing these approaches. Such sustainable valorization contributes to meeting the Sustainable Development Goals (SDGs) of the United Nations (UN).

KEYWORDS

vegetable waste, volarisation, food security, bioindicators, gut microbiome, biosorbants

1 Introduction

Food waste is a global issue that undermines our sustainable food system, causing environmental, social, and economic losses. The Food and Agriculture Organization (FAO) estimated that approximately one-third of the edible portions from food intended for human consumption, is discarded globally (Gustavsson et al., 2011). The European Union (EU) solely contributes 88.2 MT of food waste equivalent to 173 kg per capita production (Stenmarck et al., 2016). This waste can be distributed as follows: 53.2% from households, 19.27% from processing, 11.9% from catering, 10.31% from primary production, and 4.6% from distribution (Benucci et al., 2022). Food waste can occur at all stages of the food supply chain, from production to consumption. In high-income countries, 46% of waste happens at the retail and consumer levels, while in low- and middle-income countries, 50% occurs during harvesting, processing, and storage (Voge et al., 2023). FW leads to socio-economic losses in developing countries while it raises issue regarding waste management, climate change, and environmental concerns in developed countries (Esparza et al., 2020). In the US, $27 billion worth of food is waste predominantly from meat and fish (30%), vegetables (19%), and dairy products (19%) (Peira et al., 2018). A significant portion of this waste comes from unsold produce, which often gets discarded before it can be utilized (Lombardelli et al., 2022). Piirsalu et al. (2022) reported that nearly half (49%) of these unsold products were fruits and vegetables (27% fruits and 22% vegetables). These unsold goods not only cause economic loss to farmers/ retailers but also have significant environmental and ethical implications. While donating them to food banks is a viable option, perishability and national regulations often limits this practices. Besides, unsold produce processing industries generate huge amount of waste (25–30%) mostly in the form of peels, seeds, pomace, rinds, pods, cores, stones, vines and wastewater (Sarker et al., 2024). Proper disposal of these waste is a critical challenge in these sectors as it escalates the production costs. Improper disposal of waste may lead to adverse environmental impact, public health concerns, ecosystem damage, resource depletion and reduced quality of life. Many countries, such as the EU, enforced stringent regulations on waste disposal to safeguard the environment and public health (Teshome et al., 2024).

Existing studies have significantly advanced our understanding and management of food waste. However, there remains a notable gap in literature focusing specifically on vegetable waste (VW) valorization. Most of the studies primarily focus on bioactive compounds from VW, covering their extraction, utilization, and applications (Rifna et al., 2023; Pereira et al., 2022). There are several niche areas that remain underexplored but possess economic viability and feasibility (Figure 1). One such approach is the utilization of VW as substrate to promote the growth of beneficial microorganisms. These beneficial microorganisms can be utilized directly or can be harnessed to produce secondary metabolites. Other benefits are production of beneficial fungus, biotechnological media, single cell protein (SCP), and microalgae production. The phytochemicals present in VW can support the growth and proliferation of this microorganism while enhancing effectiveness and productivity.

Considering the above scenario, this review highlights vegetable processing waste as a reservoir of phytochemicals. It illuminates how the byproducts, typically discarded can be repurposed into valuable resources with diverse applications not only in food but also beyond. From bioactive compounds enhancing food and medical applications to fostering eco-friendly practices, it's a game-changer for industries and researchers aiming to unlock sustainable innovations. Each topic within this review covers the pros, cons, and future recommendations, ensuring a comprehensive exploration. Embracing the circular economy approach and sustainable practices this review is expected

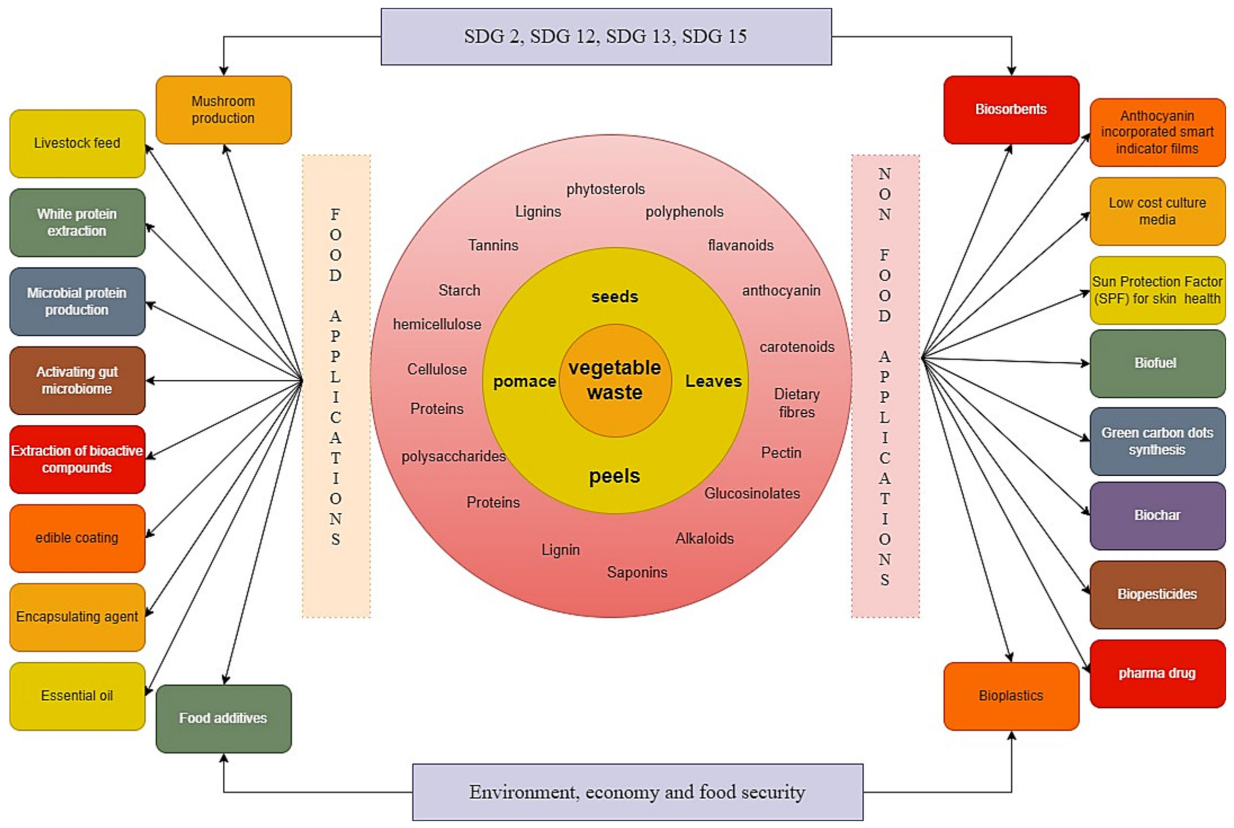

FIGURE 1
Multifaceted application of VW across various food and non food sectors.

to yield benefits far beyond waste reduction, shaping a brighter future for all stakeholders involved.

2 Literature collection and selection

Recently, the focus on turning food waste into valuable resources has gained momentum, aligning with key Sustainable Development Goals (SDGs) such as Zero Hunger, Affordable and Clean Energy, Responsible Consumption, and Climate Action. This shift aims to reduce waste while promoting sustainability. To gain a deeper understanding of progress in this area, a bibliometric analysis was conducted. This method offers both quantitative and qualitative insights into the research landscape, examining contributions from key players—journals, authors, countries, and institutions—while mapping the relationships between them. In this review, mapping was done using co-occurrence, co-authorship, and bibliographic coupling analyses with SCOPUS index database for the period from 2004 to 2024 using VOSviewer 1.6.20 software. The keywords like "vegetable waste" combined with "utilization" or "transformation" or "valorization" as subject areas.

The keyword co-occurrence map (Figure 2) revealed the major themes dominating this field, are circular economy, recycling, nutraceuticals, antioxidants, biogas, bioenergy, biofuels, and biochar. This clustering highlights that phytomolecules extracted from vegetable waste, are being repurposed across both food and non-food sectors. The co-authorship map (Figure 3) provided an interesting glimpse into global collaboration on vegetable waste valorization. India followed by China and United states has greater interaction network positioning these countries as central nodes in the research ecosystem. The bibliometric coupling map (Figure 4) highlighted the sharing of research output over the last two decades, revealing strong connections between countries involved in vegetable waste valorization. Notable contributors included India, Turkey, Pakistan, Egypt, France, the United Kingdom, Canada, China, Germany, the Netherlands, and Switzerland. These nations have been instrumental in advancing knowledge and driving innovation in sustainable practices, strengthening the global push toward a circular economy.

3 Current scenario

Food loss and waste have far-reaching consequences on the environment, depleting natural resources like land and water, and disrupting ecosystems. One of the most alarming effects is the significant emission of greenhouse gasses. According to the Food and Agriculture Organization (FAO, 2017), over 1.3 billion tonnes of food, valued at $750 billion, are wasted annually worldwide. In 2019, nearly 14% of food produced was lost or wasted globally at post-harvest level (FAO, 2019). This waste contributes to the release of 3.3 billion tonnes

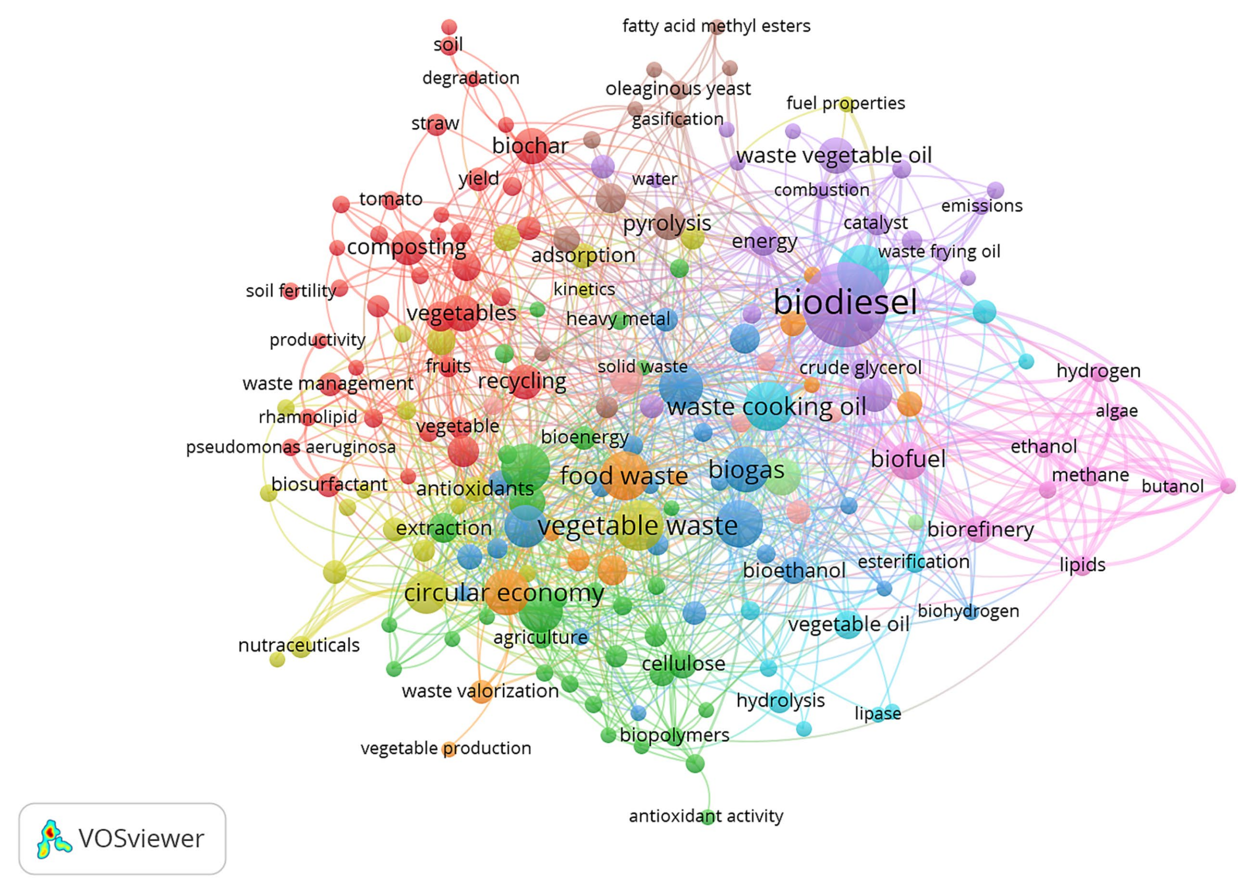

FIGURE 2
Author keyword co-occurrence network map of publications in volarisation of vegetable waste.

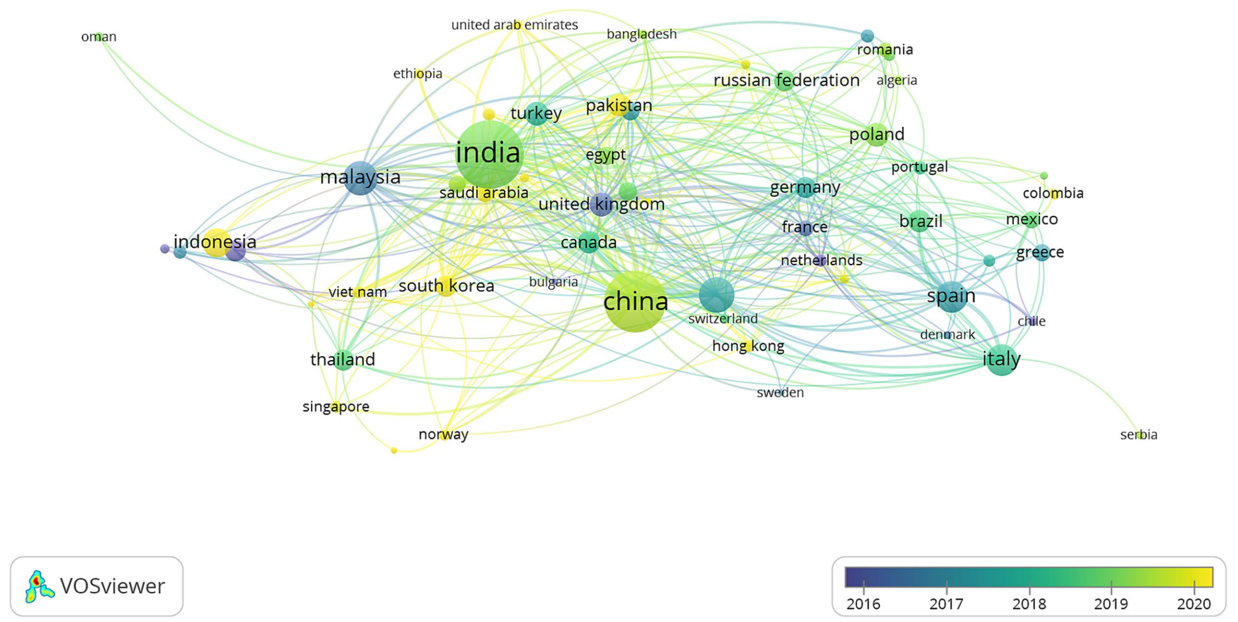

FIGURE 3
Co-authorship network map of countries collaboration in bibliography of volarisation of vegetable waste.

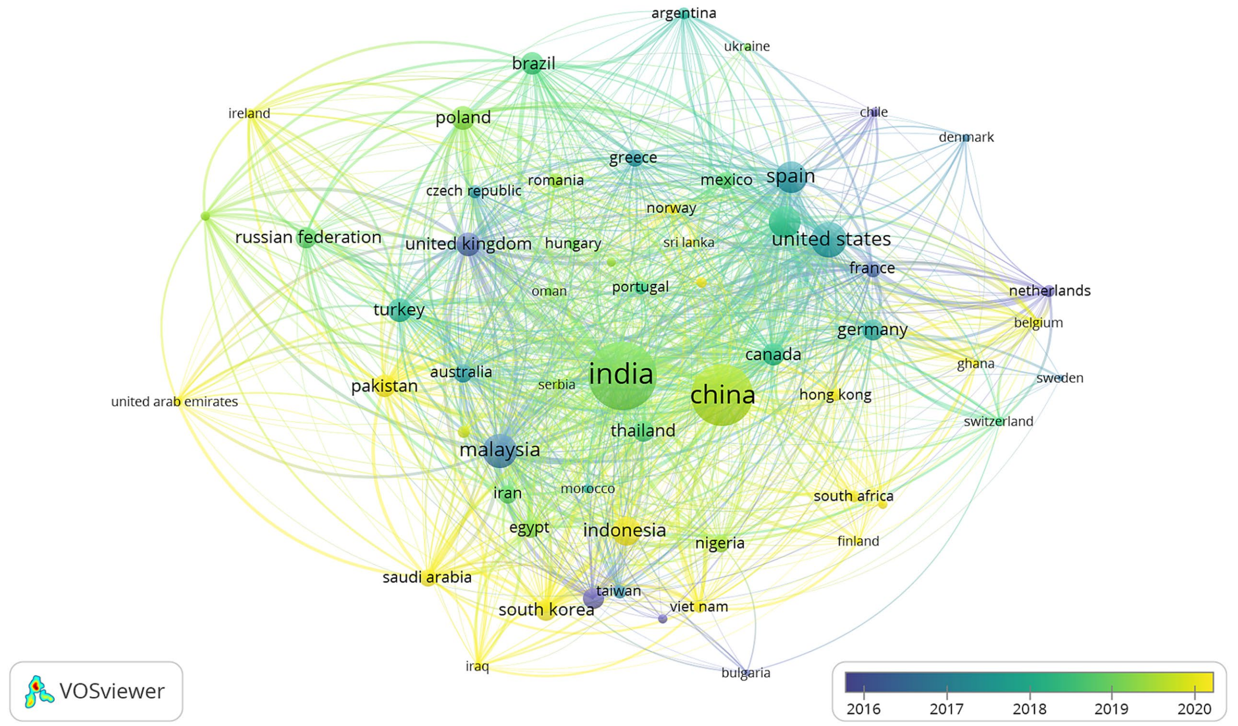

FIGURE 4
Bibliographic coupling network map among countries in publications of volarisation of vegetable waste.

of CO_2 equivalents into the atmosphere each year, amounting to 8–10% of global greenhouse gas emissions.

Food wastage is more pronounced in the United States and Asia. In the United States alone, 40% of food production is wasted, while in Asia, food wastage is particularly significant, with China and India leading in terms of volume (Gunders and Bloom, 2017). For instance, India, the second-largest producer of fruits and vegetables, sees 40% of its produce wasted–equivalent to a staggering ₹92,000 crores annually, or 1% of the country's GDP. Each Indian, on average, wastes 55 kg of food per year, as reported by United Nations Environment

Program (UNEP) in 2021. Despite this abundance, 14.3% of the population in India remains undernourished. The country ranks 111th out of 125 on the Global Hunger Index (Von Grebmer et al., 2019). The primary contributors to this waste are spoilage and insufficient cold storage during transportation, which result in loss ranging from 18 to 40% (Ghosh et al., 2017).

China faces a similar challenge due to a 23.3% increase in the area designated for vegetable production in 2020. This rise in production has led to more stringent quality screening, contributing to greater food waste and environmental constrain (Li, 2022). In response to these issues, governments and private sectors are seeking innovative solutions to recycle and repurpose food waste into valuable products. For example, a Chennai-based firm, established in 2019, introduced active packaging sachets designed to protect fruits and vegetables from spoilage and prolong their freshness, with the goal of reducing post-harvest losses in India. Such initiatives are vital in addressing the critical issue of food waste, enhancing food security, and mitigating the environmental impacts associated with discarded food.

4 Applications of vegetable processing waste

4.1 Food applications

4.1.1 VW as livestock feed

Vegetable waste (VW) is rich in bioactive compounds known to promote health of livestock (Čolović et al., 2019). Utilizing VW as livestock feed converts energy and nutrients into animal feed, recovering resources and reducing environmental impact. Bidura et al. (2021) observed that feeding laying hens with fermented carrot leaves upto 4–6% can elevate the β-carotene levels in their yolks. Ghosh et al. (2023) found that by incorporating pea pod powder from pea processing industries into the diet of Pekin ducks enhances their hypoglycemic and hypolipidemic activity. Adugna et al. (2024) observed sheep fattening by using a mixture comprising 50% pea hull, 33% Niger seed cake, 16% wheat bran, and 1% salt. Ayyat et al. (2024) noticed improved body composition and blood metabolite levels in diet of Nile tilapia (*Oreochromis niloticus*) when incorporating carrot and sugar beet leaf waste. Utilizing VW as animal feed is frequently linked with biological hazards, toxic substances, pesticide residues, and anti-nutritional factors (ANF). For instance, Allyl propyl disulfide in onion peel can trigger haemolytic anemia combined with Heinz bodies (HzB) in animal erythrocytes. VW with low sugar is preferred for cattle feed. Excess carrot and sugar beet pulp in diet of dairy animals may lead to acidosis, laminitis, and scouring owing excess fermentable sugars. Feeding cassava to animals requires careful attention and pretreatment such as cooking or heating due to the presence of linamarin, a cyanogenic glucoside that can cause poisoning. Another important consideration is the regulations governing the use of waste as livestock feed which may vary by country. Japan, South Korea, and Taiwan actively encourage FW in animal feed, while the US and Europe enforce strict restrictions. To address VW's seasonal availability, incorporating multinutrient blocks into animal diets offers a practical solution. While current research focuses on adding fruit waste to these blocks, the use of vegetable waste remains limited. So far, moringa molasses is the only vegetable extract used in blocks (Syarifuddin et al., 2022). Future studies could explore the inclusion of other vegetables rich in bioactive compounds and their effects on meat quality and shelf life.

4.1.2 VW as a substrate for mushroom production

The most common edible mushroom species whose cultivation has been tested on food waste residues include *Agaricus subrufescens*, *Agaricus bitorquis*, *Agaricus arvensis*, *Lentinula edodes*, and *Pleurotus ostreatus* (Girotto and Piazza, 2022). Mushroom species utilize these Lignocellulosic materials (peels, seeds, pods, stems, stalks, core, husks, straw) as growth substrate. Sawdust is the universal substrate in mushroom production. The drawback in this material is the limited availability of nutrients. VW based substrates can overcome this problem. Behera and Gupta (2015) reported that vegetable peel waste mediums derived from moringa, potato, carrot, bottle gourd, pointed gourd, little gourd, pumpkin, and ridge gourd could be utilized for mushroom production, although synthetic media were found to be more effective. Moringa leaf powder substrate can supply minerals, protein, nitrogen, carbohydrate, folic acid and, total sugar content in addition to reduction of spawn running time in *P. eryngii* (Sardar et al., 2022). Use of cassava peel and stem as substrate can reduce the need for expensive sterilization process, making it a cost-effective substrate for successful cultivation of oyster mushroom (Sonnenberg et al., 2015). But the primary challenge in using cassava waste is the low nitrogen content. VW can also be used to extend the shelf life of mushroom. Bernaś and Jaworska (2015) examined the shelf life of frozen *Agaricus bisporus* using onion extract. They found that soaking the mushrooms in onion extract reduced enzymatic browning, by preventing L-Dopa oxidation. As a result, shelf life can be extended to 8 months compared to typical duration of 4 months. Subsequent studies might explore the selection of vegetable waste with high nutrient content, low ANFs, and minimal pesticide toxicity. Parameters like substrate pH, temperature, humidity, and nutrient composition, particularly the carbon to nitrogen (C/N) ratio, is also need to be considered. Higher C/N ratio tends to promote mycelium growth, while a lower C/N ratio is more conducive to fruiting body development. Moreover, fungi contain a unique polymer called $(1 \rightarrow 3)$-α-d-glucans, which can bind heavy metals due to its –OH groups (Nowak et al., 2019). This characteristic can be used for decontamination, but it is not recommended for consumption. So, when selecting vegetable substrates for mushroom production, it is essential to estimate the hazardous quotient, daily intake, and total target hazard quotient. Several studies indicated the utilization of spent mushrooms as livestock feed and agricultural production promoting circular economy.

4.1.3 VW for leaf white protein extraction

Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), an enzyme constituting 30–65% of total protein, has the potential to replace plant and animal proteins in the market due to its complete and balanced amino acid profile (Grácio et al., 2023). While typically allergen-free, a rare case of asphyxia and angioedema was reported after consumption (Foti et al., 2012). RuBisCO is widely recognized for its high bioavailability due to easy proteolytic degradation, aiding intestinal absorption (Monteiro et al., 2015). Traditionally, RuBisCO has been extracted from vegetable wastes like sugar beet, spinach, kale, and broccoli leaves. Recently, researchers from Wageningen University successfully isolated RuBisCO from tomato leaves, eliminating toxins such as tomatine and dehydrotomatine to enhance its suitability for consumption (Liese et al., 2023). Unlike protein extraction from pulses, extraction and purification of RuBisCO is more complex and difficult (Pearce and Brunke, 2023). Besides, RuBisCO only constitutes around 3% of the total dry leaf weight and vary by species (Onoda et al., 2017). Once extraction and purification is standardized, RuBisCO could serve as a valuable protein supplement. RuBisCO offers potential health benefits, including anti-hypertensive properties (Udenigwe and Aluko, 2012), memory improvement (Yang et al., 2003), anxiety reduction (Hirata et al., 2007), antioxidant activity (Kobbi et al., 2015), and antimicrobial effects (Trovaslet et al., 2007). It also enhances dough binding better than gluten or pea protein (Ducrocq et al., 2020). Identifying new vegetable waste sources and refining extraction methods will support sustainability efforts like the European 'Green Protein' project, which aims to isolate proteins from sugar beet leaves for food industries.

4.1.4 VW role in activating gut microbiome for promoting human health

The gut microbiome, densely populated with microorganisms in our intestines, plays a key role in human health by interacting with host cells, dietary components, and other microbes. These interactions influence nutrition, immunity, and disease resistance, and disruptions in microbial balance can harm health (Qin et al., 2010). Numerous studies are conducted to uncover new prebiotic carbohydrates that could be sourced from agro-industrial waste (Campos et al., 2020). These oligosaccharides, primarily found in non-edible or discarded portions during processing, hold potential as functional food ingredients. Pectic oligosaccharide can be commercially extracted from citrus and apple waste. But waste from vegetables such as sugar beet, pumpkin and onions can also be utilized successfully. Aisara et al. (2021) discovered a new sugar called neokestose in red onion. This sugar has the potential to promote the growth of the *Bifidobacterium breve* strain, which is otherwise typically found in the guts of breastfed infants. Firrman et al. (2024) discovered that tomato seed extract could function as a gut microbial modulator and enhance the prebiotic potential. The extract increased the level of *Bifidobacteriaceae* taxa from 18 to 52% with the strain response differing among individuals when tested *ex vivo* conditions. Han et al. (2023) found postbiotics from melon peel extract and whey, combined with *Lentilactobacillus kefiri* DH5 strain, could suppress sarcopenia by modulating gut dysbiosis. The gut microbiota communicates with the brain via the brain–gut–microbiome (BGM) axis, and unlike drugs, long-term prebiotic consumption does not impair neurogenesis. Szewczyk et al. (2023) demonstrated that Jerusalem artichoke prebiotics combined with inulin enhanced gut diversity and supported neurogenesis in mice. This highlights the potential of VW -derived prebiotics for improving microbiota diversity, benefiting cognitive functions and the BGM axis. Computational, structural, functional, and genomic tools can validate these interactions, paving the way to identify substrates that selectively stimulate beneficial gut microbes (Table 1).

4.1.5 VW as substrate for microbial protein production

Interest in SCP production is rising as demand for protein grows due to lifestyle changes. While traditional proteins come from plants and animals, SCP, derived from algae, fungi, yeasts, and bacteria, offers an alternative solution. Its protein content varies: fungi and yeast-based SCP contains 50–55% protein with low methionine and cysteine, while bacterial SCP has 60–80% protein with high methionine and lysine levels (Patelski et al., 2015). SCP production mainly uses substrates like liquor waste, manure, cane molasses, whey, and pulp wastewater, though limited research has explored on VW. Search for cost effective substrates like potato, sweet potato, cassava bagasse is in trend among the researchers for SCP commercialisation. Sweet potato baggase utilizing *Saccharomyces* sp., *Candida utilis*, *Endomycopsis fibuligera*, and *Pichia burtonii* is the most studied area (Panda et al., 2018). Khan et al. (2022) investigated SCP production from unconventional sources such as potato peel, carrot pomace, and banana peel, finding that potato peel (82.32% carbohydrates), yielded the highest SCP. An innovative circular economy approach proposed by Anupong et al. (2022), suggested that *Streptomyces tritici* D5, a bacterium tolerant to cyanide (with a degradation potential of 100 mM), could potentially produce SCP following bioremediation of sago wastewater. Other microorganisms such *as Fusarium solani*, *F. oxysporum*, *Scytalidium thermophilum*, *Penicillium miczynski*, *Trichoderma polysporum*, *Bacillus* sp., *Klebsiella* sp., and *Pseudomonas* sp. have also shown promise in their ability to tolerate and degrade cyanide into ammonia and nitrate along with SCP. The main challenge in SCP production is the high nucleic acid content (6–10%), especially SCP produced by yeasts and fungi. The safe human consumption of this nucleic acid should fall below 2% to avoid health risks like gout, kidney stones, and elevated uric acid (Panda et al., 2018). Vegetable waste, rich in lignocellulosic material, requires pretreatment before utilization. Patelski et al. (2015) extracted 4.17 g/L of arabinose from sugar beet leaves using enzymatic and chemical treatments. Further progress in SCP production will depend on selecting efficient microbial strains and developing eco-friendly downstream processes to remove nucleic acids. SCP, with its strong nutritional profile, could replace traditional proteins in animal feed, such as fishmeal and soymeal (Figure 5).

4.1.6 VW as a source of essential oil

With increasing consumer preference for natural ingredients, essential oils (EOs) have emerged as a viable and health-conscious alternative to less favored synthetic antioxidants for preserving food (Mandal et al., 2021). Traditionally, EOs have been extracted from asafoetida, cardamom, clove, coriander, cassia bark, celery, black jeera, black pepper, black mustard, bay leaves, guggal, kokum, poppy, nutmeg, turmeric, saffron, star anise, and sweet flag. EOs can also be extracted from various vegetable-based peels and seeds such as onion, moringa, chili, pumpkin, watermelon, bitter gourd, ridge gourd, bottle gourd, sponge gourd, tomato, amaranthus, and red cabbage. Among vegetables, Alliaceae is the rich source of EO especially *Allium cepa* (82.36%), *Allium sativum* (94.63%), *Allium porrum* (86.90%), *Allium ascalonicum* (70.29%), *Allium tuberosum* (85.79%), and *Allium schoenoprasum* (76.36%). These EO exhibit antimicrobial activities when tested against *Staphylococcus aureus*, *Listeria monocytogenes*, *Salmonella* Typhimurium, *Escherichia coli*, and *Campylobacter jejuni* (Mnayer et al., 2014). The alkyl cysteine sulfoxides and phenolic content in this family impart properties such as antifungal (Kocić-Tanackov et al., 2017), antibrowning (Vazquez-Armenta et al., 2014), and antioxidant effects (Ye et al., 2013) when tested in various meat products. These characteristics make them effective for protecting food from microbial contamination and potentially useful in food processing to counteract thermal effects. The

TABLE 1 Utilization of VW as high value functional ingredient across food and non food sector.

S. no	Applications	Crop waste	Biomolecules present	Specific role	Findings	Reference
Food applications						
1	Livestock feed	Pea Pods	Fiber, Protein, Lipids, ash, minerals like K, Mg, Ca, Na, Fe, Zn, and Cu.	low-cost, nutrient-rich diet, hypoglycaemicand hypolipidemic action	5% of Pea pod powder could serve as a protein supplement in diet of White peckins duck with increased body weight.	Ghosh et al. (2023)
		Moringa leaves	Ascorbic acid, γ/α-tocopherol, iso-quercetin, astragalin, glucosinolates.	Cost-effective, improve antioxidant capability,immune response and disease resistance.	Fermented Moringa Leaves (FML) regulate the expression of immune-related genes and increase disease resistance against *A. hydrophila* via TLR2 pathway in Gibel carp (10 g FMLs per 100 g diet)	Zhang et al. (2020)
2	Mushroom substrate	Moringa leaf powder (MLP)	Vitamin C, Vitamin A, Niacin phenolic compounds, antioxidants, protein and minerals (Fe, Ca, Zn, Mg, Mn, P, and K).	Increase total yield, biologicalefficiency andnutritional quality.	Supplementing cotton waste with 6% moringa leaf powder improved yield, nutritional quality (Vitamin C and Folic acid), levels of phenols and antioxidants in *Pleurotus eryngii.*	Sardar et al. (2022)
		Vegetable waste	Cellulose, hemicellulose and lignin	High biological efficiency, increase protein content and yield.	*Pleurotus sapidus* grew well on vegetable waste when mixed with Paddy straw (30:70/20:80) and give high yield and efficacy with increased amino acid levels (Leu, Ile, Val, Thr, Met and Phe) by decreasing sugars.	Singh and Singh (2012)
3	White protein extraction	Endive leaves	Vitamins, minerals, folate and Intibin.	Foaming capacity, good solubility, form gels atlow concentrations and low temperatures	RuBisCo protein from *Cichorium endivia* on fortification with wheat dough exhibits higher protein and lysine levels with improved SDS availability.	Ducrocq et al. (2020)
4	Prebiotics	Red onion extract	Inulin-FOSs (Inulin fructo-oligosaccharides), flavonoids, alkaloids, phenolic acids.	Exhibit prebiotic properties, boosting human gut microbiota.	Inulin-FOSs extracted from red onions indicate a unique sugar neokestose on *in vitro* fermentation, which boosts *Bifidobacterium breve* and have bifidogenic effect.	Aisara et al. (2021)
		Tomato seeds	32% protein, 27% fat, and 18% fiber, and rich in phytochemicals and phenolic acids, and other bioactive compounds.	Prebiotic potential, increase *Bifidobacteriaceae,* exhibit antibacterial and antioxidant properties	Tomato seed extract from pomace boosted *Bifidobacteriaceae* levels in gut microbiota from 18 to 52%, thereby promoting human health.	Firrman et al. (2024)
5	Animal protein production	Potato peel	Carbohydrates, vitamins, minerals, and other elements such as phosphorus and potassium.	Organoleptic properties, total protein content vary with microbial source.	High Single-cell protein (SCP) can be produced from potato peel than banana peel, citrus peel, and carrot pomace which improves both the protein content and the non-essential amino acids profile in bread when applied at 4%.	Khan et al. (2022)
		Tapioca wastes	Mainly starch and enriched with several essential elements such as carbohydrate, iron, manganese, calcium	Neutral taste and outstanding thickening traits, high paste clarity.	The *Streptomyces tritici* D5 strain, extracted from soil had high cyanide resistance and degradation potential which can degrade Sago effluents substrate into single-cell protein (SCP) in 30 days with 100 mM of KCN at 35°C	Anupong et al. (2022)

(Continued)

TABLE 1 (Continued)

S. no	Applications	Crop waste	Biomolecules present	Specific role	Findings	Reference
6	Essential oil	Onion	organosulfur-containing compounds (dipropyl disulfide and dipropyl trisulphide, etc)	Used as flavoring agent, and had antioxidant and antibacterial activity.	Onion EO emulsified with 7% (w/w) sodium caseinate is stable, making it suitable for food applications despite environmental stress, and it also exhibits antibacterial activity against *Salmonella typhimurium* and *Listeria monocytogenes*.	Taghavi et al. (2022)
		Carrot and fennel green tops	Sesquiterpenes (carrot) and Phenylpropanoids (fennel)	Natural antimicrobial, particularly effective against Gram-negative bacteria, highantioxidant and anti-inflammatory activity.	EOs of carrot and fennel were significantly more effective against Gram-negative bacteria, and that obtained from *Foeniculumvulgare subsp. Vulgare var. azoricum* was more active against the yeast *Candida albicans*.	Chiboub et al. (2019)
7	Bioactive compounds	Beetroot pomace	Betacyanin, Betaxanthin	High antioxidant activity, antimicrobial and cytotoxic activity.	Beetroot powder enrich fiber content with positive effects on the farinographic and physical properties, and reduced caloric density in bakery products.	Kushwaha et al. (2018)
		Carrot Peel	α-carotene, β-carotene, lutein and α-tocopherol.	Have anti-inflammatory and antioxidant effects, antimutagenic and antitumor activity.	Carrot enriched with Vitamin A and its metabolite, retinoic acid which are vital in reproduction, lung function, good for immunity when used as Eos.	Hufnagl and Jensen-Jarolim (2019)
8	Encapsulating agent	Sugar beet	Pectin	Potent natural encapsulator for hydrophobic nutraceuticals, food and even clear beverage enrichment.	Curcumin, when encapsulated with sugar beet pectin at a 140:1 ratio, enhance encapsulation capacity to 127 mg CUR/g SBP, reduced particle size to 0.5 μm, extended shelf life to 5 days, and lowered decay rate by sevenfold.	Zagury et al. (2021)
9	Food additives	Malabar spinach	Chlorophyll, Carotenoids, flavonoids (anthocyanins and betalains)	Natural food colorant, enhancing food safety and quality	Gomphrenin I in *Basella rubra* when used as a natural colorant in ice cream, preserved 86.63% of its color after six months of storage at −20°C, without affecting the sensory quality.	Kumar et al. (2015)
		Onion	Flavonol quercetin, frutooligosaccharides and sulfur compounds	Prevention of browning caused by PPO and have high anti-oxidant activity.	Onion by-products such as juice, paste, and bagasse can offer an antibrowning effect and also reduce enzyme activity by 86%.	Roldán et al. (2008)
10	Edible films and coating	Zucchini	Pectin	Had potential antimicrobial and antioxidant properties, and used as an edible coating.	Tomato fruits coated with 5% zucchini pectin exhibit antimicrobial activity against *Staphylococcus aureus*, *Escherichia coli*, and *Aspergillus niger,* and enhance antioxidant levels by 34.32% at a 1 mg/mL coating concentration.	Jhanani et al. (2024)
		Arrow root	Starch	Used for biodegradable films preparation with better mechanical and thermal properties.	Coating plums with 2% arrowroot starch extended shelf life by reducing respiration during storage at 5°C.	Nogueira et al. (2021)

(Continued)

TABLE 1 (Continued)

S. no	Applications	Crop waste	Biomolecules present	Specific role	Findings	Reference
Non-food applications						
1	Biosorbants	Moringa seeds	Carboxyl, Phosphate, amino acids	Natural coagulant, low-cost, high adsorption capacity with fast adsorption kinetics.	The biosorption capacity of *Moringa oleifera* seed husk and pulp for the synthetic dye Acid Blue 9 (AB9) was tested at 55°C, seed pulp exhibiting the highest biosorption level of 694.2 mg/g while seed husk has the biosorption of 329.5 mg/g.	Dos Santos Escobar et al. (2021)
		Biomass	Cellulose, hemicellulose and lignin, hydroxyl, carbonyl and carboxyl groups as the main functional groups	High sorbent capacity, able to bind molecular and/or ionic pollutant species.	Vegetable wastes are a potentially useful biosorbent for removing metal ions Cu (II) metal ions and organic pigments (Orange 16 dye) from aqueous media.	Tanasa and Suteu (2022)
2	Bioindicator films	Sweet potato	Anthocyanin	Film forming property with pH indicator.	Incorporation of anthocyanin to purple-fleshed sweet potato films to monitor freshness of chicken show remarkable change in color in response to variations in pH from 1 to 12. These films remained thermally stable till 1.5% concentration.	Sohany et al. (2021)
		Onion peel extract	Anthocyanin	Low-cost, pH indicator.	Films infused with onion peel extracts were utilized to monitor milk freshness by significant color changes, shifting from light pink to colorless due to increase in acidity at pH 6.5 to 5.	Devi et al. (2024)
3	Low-cost culture media	Vegetable waste	Vitamins and minerals	Low-cost, environmentally safe raw materials, high macro and micro nutrient content.	Cabbage, beetroot and onion waste powder after addition of coconut water (cytokinin) could be used as a cheap substitute for culture media which produces growth comparable to that of synthetic media.	Subbaiya et al. (2019)
4	Skin health	Moringa seed oil	α-tocopherol, plant sterols, and fatty acid	High antioxidant activity, increase skin hydration, reduce skin erythema.	Moringa seed oil cream containsantioxidant activity with IC_{50} of 121.9 mg/mL and evenstable upto 28 days at 45°C with increased *in vivo* skin hydration level.	Athikomkulchai et al. (2020)
5	Biofuel	Vegetable waste	–	Low-cost and eco-friendly, source of alternative fuel production and also as biocatalyst in biodiesel production.	A 95% yield of biodiesel can be obtained from cooking oil waste using vegetable biowaste as catalysts generated from market, hotel and shops while bagasse, papaya stem, banana peduncle, and *Moringa oleifera* used as heterogenous catalysts.	Sathish et al. (2023)
		Potato peel	starch, (cellulose, hemicelluloses and lignin)	low cost, alternative, and renewable second-generation bioethanol	Pre-saccharification and simultaneous saccharification and fermentation (PSSF) process involving 2 h liquefaction and 10 h saccharification with 80 U/g enzymatic loading at 34°C from potato peel waste yield 104.1 g/L ethanol.	Rodríguez-Martínez et al. (2023)

(Continued)

TABLE 1 (Continued)

S. no	Applications	Crop waste	Biomolecules present	Specific role	Findings	Reference
6	Carbon dots	Onion	–	Precursor and specific for detection of Fe^{3+} ions and coupling with quinoline derivative which detects Zn^{2+} ions.	Carbon quantum dots from onions extract detect Zn^{2+} ions in blood plasma by measuring fluorescence intensity, with a high sensitivity with detection upto 6.4 µM and quantification upto 21.3 than.	Dastidar et al. (2021)
7	Biochar	Pepper straw	Cellulose, lignin and starch with high C, H and O contents (70–90%).	Have porous structures with abundant surface functional groups	Biocharfrom pepper straw showed greater DBP (Dibutyl phthalate) and DMP (dimethyl phthalate) sorption capacity at 500°C.	Yao et al., 2019
8	Organic fertilizer	Tomato pomace	Protein, lipids, fiber, minerals and bioactive compounds.	It has high organic matter andlimited toxic elements, offers better aeration of soil.	Tomato pomace as organic fertilizer combined with organic manure to increase soil properties, root (root density, root surface, and symbiotic of arbuscular mycorrhizal fungi) and growth parameters when tested in sweet maize.	Kakabouki et al. (2020)
9	Pharma drug	Jackfruit and Okra mucilage	Monosaccharides and their derivatives (Jackfruit), and Pectic polysaccharide (Okra)	Pharmacological activities, viz., antioxidant, anti-inflammatory, anti-helminthic, antidiabetic, anti-ulcerative, anti-cancer properties with excellent mucoadhesive properties	Mucilage from jackfruit and okra was used as a mucoadhesive carrier for colon-specific delivery of curcumin (CMN) in a mucoadhesive tablet (CMT). This formulation achieved a 54.35% in vitro release of CMN over 12 h and demonstrated a shelf life of approximately 4.7 years when tested in rabbits.	Kurra et al. (2022)
10	Phytoinsecticide	Vegetable waste	Antioxidants such as polyphenols	It activates baculovirus infections, as a pest control ingredient.	Extracts at 1% w/v from spent coffee, rosehip, asparagus waste, artichoke waste, beet stalks, and banana peel showed significantly higher potential against *Spodoptera littoralis*in 2nd instar larvae, with 13.61 times reduction in LC50 valuescompared to virus inoculation alone.	Martínez-Inda et al. (2023)
11	Biofilms	Brassicaceae	Phenolic compounds such as gallic acid, caffeic acid, and phenylethyl ITC	Anti-attachmentactivities against *E. coli*	Biofilms formed from extracts of young radish, radish sprout, red cabbage, and kale exhibit antimicrobial activity against *Escherichia coli* O157:H7. These extracts led to reduced viability between 5.83 and 51.5%.	Hu et al. (2019)

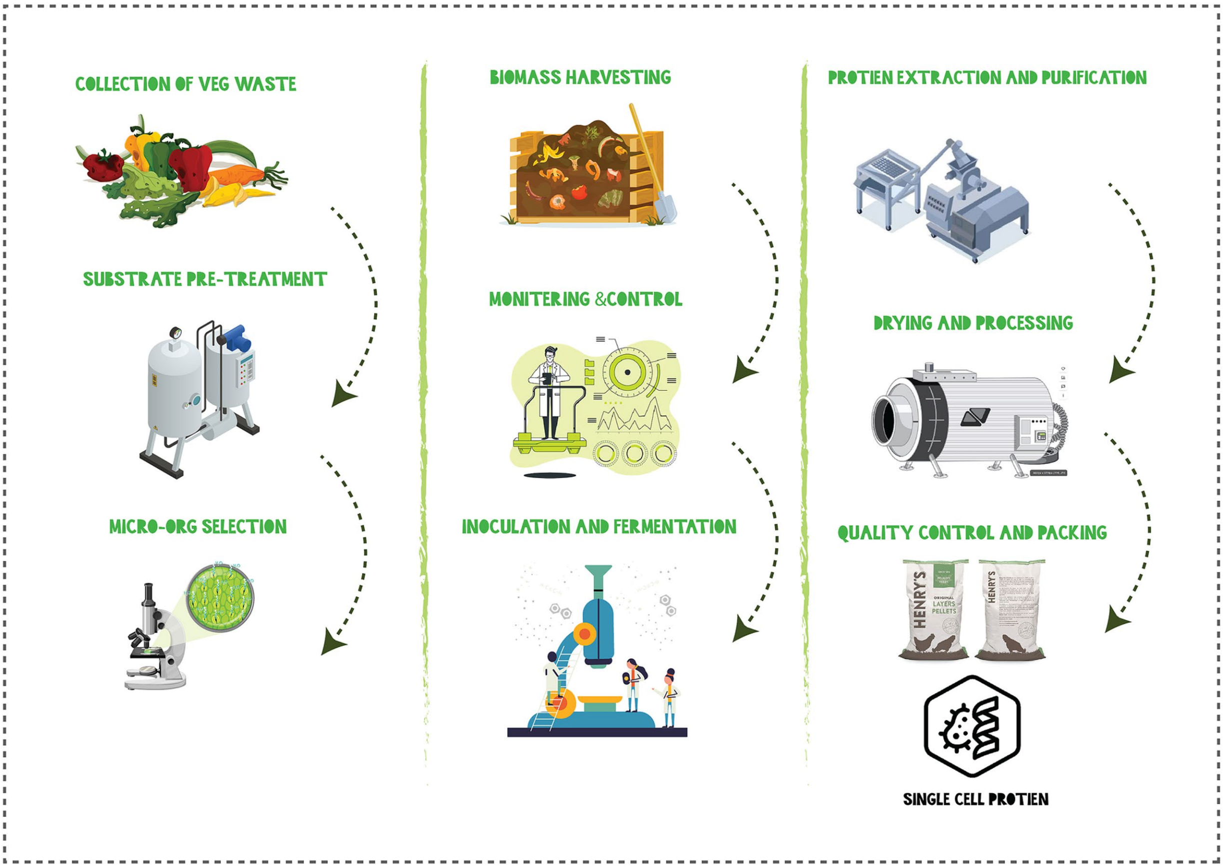

FIGURE 5
Schematic diagram of single cell protein production process utilizing sustainable vegetable waste as a feedstock.

Hexacosane (13.9%), Pentacosane (13.3%), Heptacosane (11.4%) in moringa seeds (92.3% EO), and high omega-3 and omega-6 fatty acids in Egusi seeds (*Citrullus lanatus* subsp. *Mucosospermus*) makes them promising candidate for application in food industries (Marrufo et al., 2013; Olubi, 2018). The extended shelf life and antioxidant properties of garlic EOs make them ideal for developing various processed products and nutritional supplements (Verma et al., 2023). Plant essential oils (EOs), recognized as generally recognized as safe (GRAS) by the Food and Drug Administration (FDA), show promise as flavoring agents. However, some EOs face limitations such as low water solubility and high volatility, which restrict their application in food technology. Encapsulated EOs demonstrate enhanced efficiency and effectiveness even at lower concentrations. Moreover, food products incorporating encapsulated essential oils remain stable even when exposed to environmental stresses like sunlight, heat, and freezing during storage and processing.

4.1.7 VW as a source of bioactive compounds

VW are abundant sources of phytochemicals such as dietary fibers (onion wastes, potato peels, cauliflower stems and florets, and tomato pomace), phenols (potato, cucumber, tomato, and watermelon peels), flavonoids (onion peel), enzymes (potato and cassava peels), proteins (carrot pomace, green pea pods, potato solid waste, tomato solid waste, cabbage leaves, and watermelon seeds), and organic acids, making them valuable in the pharmaceutical industry (Goswami et al., 2024). These bioactive compounds play a role in protecting against various chronic diseases. Lycopene, prevalent in peels, is a potent antioxidant, protects from eye disorders, heavy metal detoxification, Alzheimer's disease, colorectal, prostate, and gastric cancers, Type II diabetes mellitus and brain inflammation (Caseiro et al., 2020). Onion peels, skin, tops are rich source of bioactive components like quercetin and its derivatives, which are beneficial in biomedical and pharmaceutical applications (Kumar et al., 2022). Extracts from onion waste exhibit anticancer, antimicrobial, anti-obesity, neuroprotective, cardioprotective, antidiabetic, and erectile dysfunction properties (Chae et al., 2017). Pumpkin flesh, peel and seeds demonstrate potent cytotoxic activity against liver carcinoma and breast cancer cell lines (Badr et al., 2011). Pumpkin flowers and seed oil possess antifungal and antimicrobial properties, respectively, and these compounds helps lower blood pressure and chlorestrol levels (Ahmad and Khan, 2019). Further, the phytoestrogens and sterols in pumpkin seed oil have estrogen-like effects and can manage various diseases (Patel, 2013). Despite these benefits, challenges such as the heterogeneity, degradation, and perishable nature of vegetable waste hinder their pharmaceutical use. Addressing these challenges requires optimized storage conditions, effective preservation techniques to ensure product stability, and high-efficiency extraction methods for bioactive compounds. Establishing standardized protocols for quantifying and characterizing these compounds is also crucial. Overcoming these obstacles can create economic opportunities by transforming waste materials into valuable resources through sustainable practices. This could foster the development of combination products or synergistic blends of bioactive compounds. Efficient extraction techniques will further enable the use of these compounds in medicinal treatments and food research, paving the way for functional foods.

4.1.8 VW as encapsulating agent

Microencapsulation technology is a specialized method for preserving valuable bioactive compounds from degradation. This is achieved by encasing solid, liquid, or gaseous materials in a continuous film coating, forming capsules that range in size from micrometers to millimeters (Qin, 2016). Various encapsulating materials are employed in this process, including: 1. Polysaccharides such as Arabic gum, maltodextrin, modified starches, chitosan, and pectin 2. Proteins such as whey protein isolate and concentrate, gelatin, soy protein, casein, and milk serum 3. Lipids such as vegetable oil and hydrogenated fats. Pectic polysaccharides are the widely employed encapsulating agents, among other substances (Carbonaro et al., 2015). Pectin derived from sugar beet rich in homogalacturonan (HG), rhamnogalacturonan I (RGI), and rhamnogalacturonan II (RGII) polysaccharides, has superior emulsification properties compared to citrus pectin. Studies by Zagury et al. (2021) showed effective encapsulation of curcumin [bis (4-hydroxy-3-methoxyphenyl)-1,6-heptadiene-3,5-dione] with sugar beet pectin, resulting in extended half-life and no crystalline structures. Recently, the focus has shifted toward using vegetable proteins as encapsulating agents due to their biodegradability, biocompatibility, and amphiphilic nature (Islam et al., 2023). Plant-based proteins, especially pea protein, have gained popularity in food systems due to their cost-effectiveness, abundance, and desirable functional properties (like foaming, stability, and emulsification), attributed to albumins, globulins, vicilins, and legumins (Hadidi et al., 2022; Burger and Zhang, 2019). Pea protein isolate (PPI) is comparable to soy protein isolate (SPI) in amino acid content and digestibility, and its effectiveness can be enhanced by coacervating with pectin to improve stability. Pea protein nanocarriers also protect cholecalciferol (vitamin D3) from UV radiation. Plant proteins and pectins are vegan, Kosher-Parve, Halal, and allergen-free, making them attractive for the global food industry, especially as consumers demand clean-label products with natural ingredients. The sustainability and health benefits of these encapsulants drive innovation in developing commercially viable processes that align with these principles.

4.1.9 VW as food additives

Food additives play a crucial role in improving food safety and quality by reducing perishability, preventing microbial spoilage, enhancing color and flavor, and adjusting acidity (Bearth et al., 2014). These functions help minimize food waste while increasing the variety of products available to consumers. Initially, “E numbers” were regarded as indicators of safety; however, they are now often met with skepticism due to the growing “clean label movement, “which emphasizes simple ingredient lists (Asioli et al., 2017). While consumers generally prefer foods without additives, they tend to favor natural additives over synthetic ones, driven by concerns that synthetic additives may pose health risks, including carcinogenic, mutagenic, and allergenic effects (Ueda et al., 2022). Natural food additives derived from plants, fruits, and spices are recognized for their beneficial properties and can be categorized into antioxidants, antimicrobials, flavorings, and colorants (Novais et al., 2022). For example, fructo-oligosaccharides from onion, garlic, beetroot, tomato, Jerusalem artichokes, and cassava waste serve as natural sweeteners in functional foods, replacing synthetic options. Thiols from onion bagasse act as anti-browning agents for fresh-cut avocado, while natural food colors—including anthocyanins, betalains, chlorophylls, and carotenoids—can be extracted from vegetable peels and pomace to serve as sustainable alternatives to synthetic dyes. Roldán et al. (2008) demonstrated that onion bagasse significantly reduces enzymatic activity (by 86.06%), making it a promising natural anti-browning alternative for the food industry. The extraction of natural pigments such as chlorophyll, carotenoids, anthocyanins, and xanthophylls has gained increasing attention in food science due to their bioactive properties. Traditional extraction methods, including maceration and Soxhlet extraction, often rely on organic or inorganic solvents, making them costly, environmentally unfriendly, and inefficient due to low extraction yields and prolonged processing times. To address these limitations, various green extraction techniques have been developed, including superfluid extraction, ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), pressurized liquid extraction (PLE), and enzyme-assisted extraction (EAE). Lombardelli et al. (2020) employed EAE using a mixture of polygalacturonase, pectin lyase, cellulase, and xylanase to enzymatically degrade plant cell walls, enhancing carotenoid release from unsold tomatoes. This method achieved high carotenoid recovery, yielding 4.30 ± 0.08 mg lycopene/kg tomato/U and 5.43 ± 0.04 mg lycopene/kg tomato/U of careteniods and carotenoid contanining chromoplast, respectively. Similarly, high recovery yields of betalains from sugar beet and chlorophyll from spinach were demonstrated using enzymatic extraction by Lombardelli et al. (2021) and Mazzocchi et al. (2023). Despite their general safety, natural additives also require further studies to assess their toxicity, carcinogenicity, and overall health impacts. While natural biocolorants offer numerous advantages, several challenges remain, including stability under heat, pH variations, and light exposure. Additionally, natural additives often need to be used in larger quantities than synthetic ones, which may affect food appearance, taste, or texture, raising concerns about cost-effectiveness. The absence of specific legislation for natural additives—currently regulated similarly to synthetic ones—further complicates the approval process for new compounds. Nevertheless, natural additives are increasingly viewed as the future of food preservation, offering a promising avenue for extending shelf life and reducing food loss.

4.1.10 VW based edible coating to improve quality

Creating biodegradable edible films and coatings offers a sustainable and eco-friendly alternative to synthetic chemicals and petrochemical plastics. These films provide a thin protective layer on fruits and vegetables, effectively controlling moisture loss and regulating gas exchange to maintain produce integrity and freshness (Ju et al., 2019). A significant advantage of edible coatings is their consumability alongside the coated produce, helping to retain original nutrients (Cheng et al., 2023). Pectin, due to its natural abundance, low cost, and renewability, is a crucial component for developing edible coatings (Valdés et al., 2015). Starch from various sources, including tapioca, corn, sweet potato, and rice, has also been employed in producing edible films. For example, Jhanani et al. (2024) demonstrated that a 5% pectin coating from zucchini exhibited antimicrobial properties against pathogens like *Staphylococcus aureus*, *Escherichia coli*, and *Aspergillus niger*. The coating also displayed antioxidant activity (34.32% at 1 mg/mL) and effectively delayed ripening, extending the shelf life of tomatoes without compromising their physicochemical properties, indicating its potential for commercial scalability. In another study, Nogueira et al. (2021) applied a 2% arrowroot starch coating to plums, which adhered well, reduced mass loss, and decreased respiratory rates at a storage temperature of 5°C. Sweet potato starch, with a high starch content (58–76% on a dry basis), proves ideal for creating clear and flexible coatings (Issa et al., 2018). Oyom et al. (2022) incorporated cumin oil into sweet potato starch to enhance pear preservation, effectively reducing rot lesions caused by *Alternaria alternata* and delaying changes in color, firmness, and chlorophyll degradation. This coating improved both the storage quality and sensory properties of the pears compared to uncoated samples, indicating its potential to address postharvest losses and promote agricultural sustainability. Additionally, Saberi et al. (2018) utilized a blend of pea starch and guar gum, combined with shellac and oleic acid, in a layer-by-layer approach to protect the postharvest quality of 'Valencia' oranges. This approach effectively reduced respiration rates, ethylene production, weight loss, firmness loss, peel pitting, and decay rate, thereby preserving the fruit's overall flavor and freshness. Notably, bilayer coatings proved more effective than single-layer coatings, although higher ethanol levels could lead to off-flavors. Edible films and coatings must comply with specific guidelines governing food additives, ensuring that all chemicals and additives used are recognized as Generally Recognized As Safe (GRAS) and incorporated at levels recommended by the FDA for safety. Each country has unique regulations regarding food packaging and approved ingredient levels. The intended function, dosage, and toxicity level of food additives in the edible matrix must be clearly indicated in the label. Further, Additives should not alter the food's sensory appeal, physical attributes, or chemical characteristics. When protein-based edible films and coatings, such as those using gluten, whey, casein, soy protein, and peanut protein are used must be clearly mentioned in the label due to their potential to trigger allergic reactions (Carpena et al., 2021).

4.2 Non-food applications

4.2.1 VW as sorbents in decontaminating heavy metals

The lives of the people living near textile and paper manufacturing industries are at risk due to severe contamination of the environment with dyes, oils, and heavy metals (Chong et al., 2023). Researchers are currently seeking affordable, effective, and simple methods for heavy metal removal. One promising strategy is the use of agricultural waste, which can be converted into biosorbents. This technology adheres to the principles of green chemistry that utilizes renewable materials as feedstock. Sánchez-Ponce et al. (2022) investigated the sorption capabilities of various agricultural wastes and discovered that broad bean pods are highly effective in absorbing metal ions, achieving 91.5% efficiency for Pb (II), 61.7% for Cd (II), 40.7% for Co (II), and 39.7% for Ni (II). Dos Santos Escobar et al. (2021) examined the use of moringa seed husk and pulp in removal of Acid Blue 9 (AB9) dye with maximum sorption capacities of 329.5 mg g−1 for the seed husk and 694.2 mg g−1 for the pulp at 55°C, by utilizing green synthesis method. In recent years, these biosorbents are employed in detoxification of human body. Vázquez-Durán et al. (2021) utilized waste from kale and lettuce to eliminate aflatoxin B_1 (AFB_1) from the digestive tract. The study achieved high removal efficiencies of 93.6 and 83.7% with kale and lettuce respectively, through formation of AFB1-chlorophyll complexes. Biosorbents, due to their high efficacy and cost-effectiveness, could serve as a viable alternative for environmental remediation (Singh et al., 2020). Future research could explore the utilization of these sorbents for the remediation of pollutions caused by pesticides, fertilizers and nuclear waste.

4.2.2 Developing meat freshness indicating biofilms by incorporating VW based biopigments

Smart packaging integrates sensors and indicators within packaging systems to monitor food quality, with a focus on pH levels and freshness (Rahimah et al., 2020). This technology is commonly applied in packaging perishable goods like animal meat, susceptible to microbial growth leading to protein breakdown and amine production. As deterioration progresses, pH levels shift from 5.8 to 7.4, a change detected by pH indicators that respond by changing color (Wang et al., 2017). These indicators are halochromic substances that interact with hydrogen and hydroxide ions, causing color alterations based on solution acidity or alkalinity. Unlike synthetic indicators that release harmful chemicals such as phthalic anhydride, the preference has shifted toward plant-based anthocyanin indicators. Anthocyanins exhibit a range of colors depending on pH: red predominates at pH values below 2 due to the flavylium cation, shifting toward a purple/blue hue at pH 2–4 (quinoidal base), colorless at slightly acidic/near-neutral conditions (carbinol pseudo-base) and a green-yellow hue at pH beyond 7 (Wahyuningsih et al., 2017). The color of anthocyanidins varies according to the number of hydroxyl groups in their molecules. Anthocyanins from purple yam extract, red cabbage extract, onion peel, purple sweet potato peel, roselle calyx, betalins from Basella stem, beetroot peel have the huge potential to be exploited as color sensitive indicator packaging materials (Chaari et al., 2024). Stability of anthocyanin pigments highly depend upon source material. Identifying stable pigment or improving the stability by incorporating nanomaterials or biopolymers into matrix can improve functionality and sustainability of films. Further advancements in sensor technologies and mobile connectivity, hold promise for future of anthocyanin-based smart packaging.

4.2.3 VW based low-cost culture media that substitute high-cost chemicals

Searching for components that substitute high-cost synthetic chemicals involved in the preparation of aseptic/microbial media is the need of the day. The microbial media can be utilized in either way: for supporting microbial growth or for synthesizing microbial compounds (Dos Santos Escobar et al., 2021). Waste from tomatoes, onions, carrots, pumpkins, cabbage, potatoes, drumsticks, and cauliflower can be utilized in microbial media formulations. These wastes are loaded with carbohydrates and proteins, making them valuable sources of carbon and nitrogen (Jadhav et al., 2018). Some waste for instance, onion peels in BCO (Beetroot, Cabbage and onion peel) can supply micronutrients essential for growth of plants in culture medium (Subbaiya et al., 2019). The outworks from this study was comparable to those achieved with commercial media. This reinforces the idea that VW is a powerful substitute for commercial media. High value secondary metabolite (pigments, acids, enzymes) that have medical, textile, food applications can be produced from microbes with less cost VW media. Jeong et al. (2023) cultured *Lactobacillus plantarum* using waste from kimchi, cabbage and onion. The results from this work clearly indicate that only the production of lactic acid increased and not the number of cells. Further, they noticed an increased antibacterial activity and anti-inflammatory response while using this waste as a substrate. Application of VW in microbial culture medium, though, many studies have been conducted, it is still in infancy stage. Not much literatures available in commercial standarisation of media and sources; secondary metabolite quantification and comparison with commercial media. Therefore, VW holds a significant potential as an ingredient in media formulations.

4.2.4 VW based phytochemicals in promoting skin health

Sun burn, skin darkening and cancer are the harmful dermatological effects resulting from exposure to ultra violet (UV) radiation. In order to prevent this, synthetic UV filters containing dangerous oxybenzone were used without much awareness. Organic filters synthesized by extracting phytochemicals from VW can be a remedy to this problem as they exhibit radical scavenging property (Valisakkagari et al., 2024). These phytochemicals after separation from waste can be encapsulated and tested for its sun protection factor (SPF). But this is not the same in most of the cases as findings by Messias et al. (2023) indicated that SPF in encapsulated onion peel extract (36.11 SPF) is much lower than the unencapsulated extract (60.24 SPF). The compound revesterol is the key ingredient here. Other waste from vegetables such as kale, beetroot, pumpkin, cauliflower also finds their place in cosmetic sector due to their high flavonoids and phenols. Another complication faced by young and adult people were early signs of aging triggered by oxidative stress. Collins et al. (2022) stated that oral consumption of tomato extract for 8 consecutive weeks resulted in skin lightening and hydration. Focussing on hydrating creams, most of them utilize vegetable oil as functional ingredient for solving dehydration problems. Athikomkulchai et al. (2020) reported that moringa seed oil possess skin hydrating property and reduced inflammation of skin. Vegetable bioactive ingredients finds application in hair care also. It is interesting to note that oil from pumpkin seed stimulated hair growth when applied topically in male rats thereby reducing baldness (Hajhashemi et al., 2019). To conclude, sunscreens manifest major importance these days owing to increased global warming. Various VW can be screened for their SPF and can formulated into product through micro/nano encapsulation or molecular infusion techniques.

4.2.5 VW based biofuel generation as a substitute for fossil fuel

The declining global oil resources, fluctuating crude oil prices, and the environmental impact of fossil fuels have heightened interest in biofuel production and utilization. Biofuels are often viewed as a viable alternative to fossil fuels to mitigate climate change, enhance energy security, and reduce harmful emissions from transportation. VW are rich source of cellulose and hemicelluloses with C/N ratio over 30% can successfully converted into biomethane, bioethanol, and biobutanol. To produce biofuels, macromolecules like starch, protein, and lipids must be hydrolyzed into micromolecules such as glucose and amino acids, which microorganisms can use to generate biofuel. Hydrolysis followed by fermentation is a common process, with hydrolysis being quicker and easier for carbohydrate-rich substrates compared to proteins and lipids (Wei et al., 2016). Various pretreatment methods are employed including physical size reduction (physical pretreatment, Han et al., 2023), chemical depolymerization (chemical pretreatment, Van Ginkel and Logan, 2005), and enzymatic action (enzymatic pretreatment, Zhang and Lynd, 2006). VW and waste water from carrot, beetroot, cassava, onion, sweetpotato, and potato possess significant biohydrogen potential (Zhang et al., 2022; Saidi et al., 2020). Used vegetable oil and waste such as cassava starch, corn stover, pineapple waste, papaya stem, banana peduncle, and *Moringa oleifera* are widely studied for biodiesel production (Sathish et al., 2023). Bioethanol, produced by fermenting the sugar and starch components of agricultural wastes, is the most widely consumed liquid biofuel globally. Commercial production of bioethanol often uses vegetable waste-based sources such as potato peels, cassava peel, carrot pomace, spent sugar beet pulp, sweet potato peel and yam as renewable feedstock (Kitson-Hytey et al., 2024). Anaerobic digestion of agricultural waste generates biomethane, with studies showing significant potential from cassava, arrowroot and sugar beet leaves (Lien et al., 2018). While agricultural residues are favored for economic and environmental reasons, the debate continues overusing vegetable waste compared to municipal and wood waste. Optimizing production parameters through statistical and mathematical methods ensures lower energy consumption, shorter residence times, reduced material usage, and higher product yields (Figure 6).

4.2.6 VW derived green carbon dots in nano delivery systems

The photoluminescent properties of carbon dots (CDs) and their ability to emit multispectrumat various wavelengths make them highly valuable in the biomedical field for sensing, detection, and imaging. The most notable feature is that the spectrum can be tuned according to wavelength (Molaei, 2020). CDs hold significant potential in cancer research by offering a targeted delivery system that could replace conventional radiotherapy (Badıllı et al., 2020). Green extraction methods are preferred over conventional methods to avoid metal toxicity. Various cost-effective and eco-friendly strategies have been developed using non-edible food parts like peels, starch, and seeds from onion, pumpkin, watermelon, tapioca, potato, arrowroot, sweet potato and garlic (Raveendran et al., 2022; Krishnaiah et al., 2024). Extensive literature highlights the use of onion peel-derived CDs in the medical field. For instance, Dastidar et al. (2021) used onion peel CDs to estimate Zn^{2+} ions in blood plasma, which can prevent neurological disorders, diabetes, epilepsy, and Parkinson's disease. Monte-Filho et al. (2019) used onion peel CDs to measure vitamin content in multivitamin tablets, while Shahraki et al. (2019) demonstrated their anticancer activity against MCF-7 breast cancer cells. Majumder et al. (2021) developed functional carbon nano-onions (CNOs) that deliver drugs directly to the brain through nasal, bypassing the blood–brain barrier. Dinç (2016) reported the

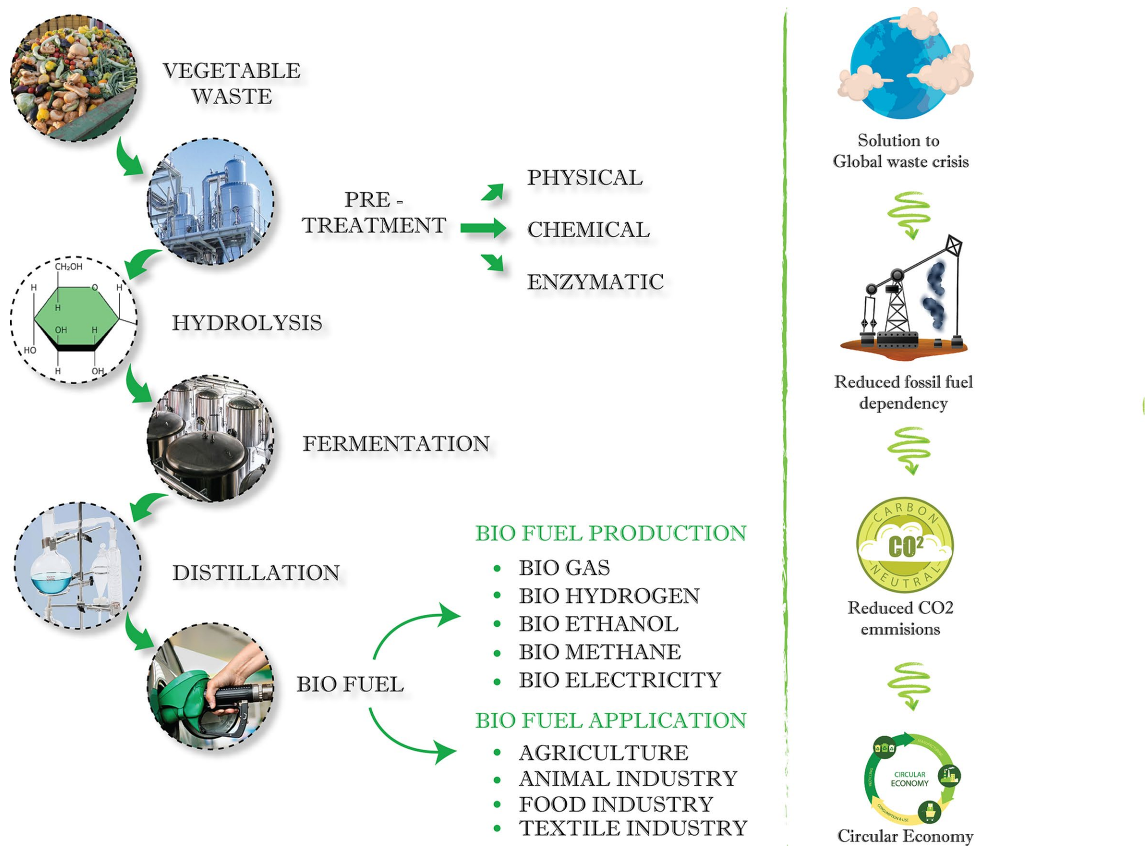

FIGURE 6
Volarisation approach of vegetable waste-based biofuel as a sustainable alternative to fossil fuels toward the zero waste champaign.

first CDs from sugar beet molasses for estimating vitamin and antibiotic properties. The benefits of quantum dots (QDs) for drug delivery include their large surface area, which facilitates easy crossing of cell membranes and provides multiple sites for drug attachment. However, challenges such as CD stability at higher pH levels, leakage testing before delivery, cytotoxicity assessment, and drug bioavailability must be addressed. Beyond drug delivery, CDs are useful in environmental monitoring for detecting heavy metal ions, phenol, pesticides, and nitroaromatic explosives. Advances in bioprobes have further enhanced the applications of CDs.

4.2.7 VW based activated carbon for soil amendments

Biochar, a renewable carbon produced from organic material through pyrolysis, is increasingly recognized for its potential to address climate change, enhance soil health, and boost agricultural productivity (Bolan et al., 2022). Biochar contain functional groups –COOH, –OH, –C=O, and –CHO, which enhance the binding of inorganic contaminants, thereby improving soil fertility (Mandal et al., 2021). These functional groups, combined with the presence of alkali metals in the feedstock, enable their application in acidic soil environments by sequestering H^+ ions from the soil solution (Yang et al., 2018). The porous structures in biochars provide habitats for microorganisms that can mitigate heavy metal and environmental pollution (Wang et al., 2023). Additionally, organic coatings on biochar surfaces reduce hydrophobicity and enhance nutrient retention, facilitating slow-release nutrient delivery (Edussuriya et al., 2023). Various types of feedstocks are utilized in biochar production, including agricultural and animal waste such as rice straw, corn cobs, wheat residues, animal waste, sewage sludge, municipal solid waste, and biogas residues (Kumar et al., 2023). Literatures on biochars from VW is scarce. Pradhan et al. (2020) produced biochar of particle size <75 μm and 75–125 μm from vegetable sources like cauliflower, cabbage, banana peels, and corn cob residues at 300°C to 600°C temperatures. They identified cauliflower and banana peels as optimal feedstocks though mixed vegetables also exhibited promising characteristics. Stylianou et al. (2023) suggested that biochar derived from tomato pomace, obtained at temperatures of 350°C and 550°C, could serve as organic amendments/enhancers to enhance agricultural soil fertility. Studies by Ebrahimi et al. (2016) suggests the possibility of utilizing biochar to manage nematode populations. However, further investigation is required to determine the ideal dosage for effective nematode control. Most of the studies conducted on this subject has taken place in controlled environments such as laboratories and greenhouses, over brief periods. Keske et al. (2020) emphasized the importance of long-term studies to validate the results, to assess any negative impacts of biochar application in soil, to confirm the efficacy of vegetable waste biochar, to estimate cost analysis in future studies. Another limitation of biochar is the potential environmental hazards posed by the presence of heavy metals and Polycyclic

Aromatic Hydrocarbons (PAHs). Biochars have the potential to be utilized in aquatic vegetable cultivation as well as in root and tuber crops. Reviews by Edussuriya et al. (2023) and Wang et al. (2023) extensively discuss application of biochars on these contexts. Moreover, it is essential to investigate interaction of microorganisms, plants, and soil, through physiological, proteomic, and metabolomic approaches.

4.2.8 VW based organic fertilizers in substituting chemical fertilizers

The impact of chemical fertilizers on human health, animal welfare, and environmental sustainability has driven research toward minimizing their use without compromising agricultural yield. This pursuit seeks safe, cost-effective, and organic alternatives. Agricultural waste, particularly VW, which accounts for over 60% of waste generated, is rich in bioactive compounds, leading to increased interest in VW-based biofertilizers. The porosity of organic fertilizers enhances soil quality by providing a habitat for beneficial microorganisms. Combining organic and inorganic fertilizers can optimize nutrient release in the soil, ensuring that nutrients are available gradually and effectively. For instance, tomato pomace, containing high levels of carbohydrates (25–50%), has been explored as an organic fertilizer for crop plants (Kakabouki et al., 2020). Onion peel juice concentrate at 1 to 2% can act as stimulant and enhance the performance of Bermuda grass, lettuce, and bok choy. Fruit and vegetable waste (FVW) has the potential to function as eco-enzymes Fadlilla et al. (2023). These eco-enzymes support plant growth due to their functional enzymes—such as amylase, lipase, protease, cellulase, and caseinase—and secondary metabolites like flavonoids, quinones, saponins, alkaloids, and cardioglycosides. VW based biofertilizers can be effectively utilized in hydroponic system. Siddiqui et al. (2023) successfully utilized organic liquid fertilizers derived from fruit and vegetable waste on various crops, including lettuce, cucumber, and cherry tomatoes. Numerous patents have been registered for techniques that convert FVW into organic fertilizers, highlighting the innovative potential in this area. The use of VW for organic fertilizers opens new research horizons, providing opportunities to explore diverse microorganisms. Future studies could aim to establish standardized microbial consortia for producing VW-based biofertilizers. Standardization is critical and should encompass raw materials, digestate types, microbial sources, preparation methods, application modes, timing, and cultivation techniques, as emphasized by Sharma et al. (2023). Evaluating the efficacy of VW against soil-borne pathogens and nematodes is essential, alongside conducting cost–benefit analyses to inform decision-making. Legislative constraints regarding the use of FVW-based fertilizers pose challenges to commercialization. However, the commercialization of VW-based fertilizers, similar to sewage sludge and animal manure, is recommended, provided that rigorous safety testing is conducted to meet regulatory standards. By addressing these considerations, the potential of VW as a sustainable alternative to chemical fertilizers can be fully realized, contributing to a greener and more sustainable agricultural future.

4.2.9 VW as pharma drug

Utilizing VW polysaccharide as platform molecules over fossil-based resources have significant advantage over health, environment and cost. They can serve as a starting material, reagents, and solvents, intermediates, APIs, or excipients while also enhancing the organoleptic properties, patient acceptance, performance of formulations (Choudhury et al., 2022). Starch from potato, cassava, yams, arrowroot finds application as bulking agent, binder, disintegrant, and film-forming agent. Cellulose from pomace such as tomato, cucumber, carrot as gel-forming agents and polymeric carriers for controlled drug release (Zhang et al., 2019). Hemicellulose from pulp can be utilized as hydrogel forming agent (Berglund et al., 2020). Konjac galactomannan from konjac tubers and xanthum gum can be used forms a network of intermolecular hydrogen bonds that stabilize the gel phase and alter drug release characteristics. Pectin from green beans, carrot, tomato and potato peels, and okra pods can be used in tablets targeting colon, transdermal patches, ophthalmic preparations (Owusu et al., 2021) Mucopolysaccharides from mucilage of unripe okra pods can be used as effective emulsifying agents, adhesives, binders, and disintegrating agents (Dantas et al., 2021). Kurra et al. (2022) utilized mucilage blend of jackfruit and okra for colon specific delivery of active ingredient curcumin (CMN) as mucoadhesive tablet achieving 54.35% with *in vitro* release of CMN in 12 h as mucoadhesive tablet. Xyloglucan from tomato, cabbage, lettuce, eggplant can be used as stabilizer, thickening agent, and gelling agent (Kim et al., 2020). Inulin obtained from peels and seeds of artichoke, onion, garlic, bitter gourd can be used in diagnosis of glomerular filtration rates (Afinjuomo et al., 2021). Most of these vegetables are rich source of polysaccharides, around 40–67% cellulose in their composition. This cellulose after pretreatment yields high quality microcrystalline fibers a filler in tablet formulation (Kian et al., 2020). The primary challenge in using VW as an excipient lies in meeting rigorous purity standards set by pharmacopeias. A prominent example illustrating this challenge occurred in the 1990s, when contaminated glycerol containing diethylene glycol led to the tragic deaths of at least 80 children in Haiti. Besides, natural excipients have the potential to interact with active ingredients and compromise their efficacy. Only a few authorities, such as the European Pharmacopeia, United States Pharmacopeia, and WHO's International Pharmacopeia, have specified these impurities (Boonen et al., 2014). Common impurities include heavy metals, PHAs, mycotoxins, and residual solvents, each requiring individual evaluation (EMA, 2009). Moreover, researchers must carefully consider the specific dosage and route of administration for drugs containing these impurities. Higher levels of impurities may be acceptable for topical applications compared to oral ingestion. Efforts should focus on creating a priority list of relevant impurities to ensure the safety of these excipients. Another significant challenge for pharmaceutical companies is ensuring compliance with labeling, composition, and marketing regulations, emphasizing efficacy, safety, and quality assurance. Additionally, it's crucial for consumers to use supplements only under the guidance of healthcare professionals.

4.2.10 VW based phytopesticide as an alternative to synthetic pesticides

Chemical insecticides have significantly increased agricultural production by effectively deterring pests at a relatively low cost. However, their widespread and unregulated use has led to numerous issues, including environmental pollution, depletion of the ozone layer, resistance development in target pests, reduction in non-target species, and adverse health effects on humans (Serrão et al., 2022). Recent studies have explored the potential of waste materials—such as spent coffee grounds, rosehip, asparagus waste, artichoke waste, beet stalks, and banana peels—to produce *Spodoptera littoralis* Nucleopolyhedrovirus (SpliNPV) baculovirus, which exhibits a 50% lethality rate against *Spodoptera littoralis* (Martínez-Inda et al., 2023). Additionally, VW extracts can be used to culture entomopathogens and baculoviruses, providing an eco-friendly alternative to conventional insecticides. For instance, Abiy and Tesfaye (2019) successfully cultured the entomopathogenic fungus *Metarhizium anisopliae* from vegetable waste. Phytopesticides extracted from vegetable waste function through various mechanisms, such as acting as repellents, disrupting protein structures, inducing metabolic disorders, causing paralysis, poisoning specific targets, exerting inhibitory actions at multiple sites, and releasing neuromuscular toxins and bioactive compounds (Ayilara et al., 2023). Specific extracts, particularly from onion and garlic, are rich in organosulfur compounds like allicin, ajoene, diallyl sulfide (DAS), diallyl disulfide (DADS), diallyl trisulfide (DAT), and S-allylcysteine (SAC). These compounds can affect the insect nervous system, leading to altered locomotion, muscle contractions, and paralysis (Kovarovič et al., 2019). Similarly, capsaicinoids (including capsaicin, dihydrocapsaicin, and nordihydrocapsaicin) and glucosinolates (such as gluconasturtin, glucotropaeolin, and glucoaubrietin) have been found to cause larval intoxication and lethality (Claros Cuadrado et al., 2019). To maximize the effectiveness of these natural alternatives, efforts should focus on standardizing dosages, studying their mechanisms of action, conducting comprehensive toxicological studies, and examining the interactions among insects, plants, and humans. This type of research will be crucial for developing safe and effective biopesticide solutions that can help mitigate the environmental and health impacts associated with chemical insecticides.

4.2.11 VW as source of bioplastics

The excessive use of plastics has shifted attention from macroplastics to microplastics and nanoplastics, which contribute to environmental pollution in marine and terrestrial ecosystems, pose health risks to humans and animals, and drive climate change (Yin et al., 2013). In response, developed countries like the EU and the US have adopted circular economy policies to mitigate plastic usage and its impacts (Visco et al., 2022). Researchers are increasingly exploring renewable plastics as alternatives to conventional ones. Studies have shown that VW —including tomato pomace, onion peels, watermelon rinds, cassava peels, potato starch, arrowroot starch, carrot pomace, asparagus peels, artichoke leaves, and pea pods—can be utilized for this purpose. These wastes can be categorized into starch-based materials for thermoplastic production and protein-based waste for plasticizer production. Additionally, they are used to produce microcrystalline cellulose, nanocrystalline cellulose, and nanofibers with enhanced mechanical properties. For example, microcrystalline cellulose films made from cassava starch exhibit similar properties to starch films but with increased hydrophobicity (Liu et al., 2024). Non-lignocellulosic biomass, such as fruit peels and pomace extracts, is also gaining traction in active food packaging due to its antimicrobial and antioxidant properties. Hu et al. (2019) found that biofilms made from radish, kale, and cabbage extracts exhibited antimicrobial activity against *E. coli* O157: H7, attributed to phenolic compounds like gallic acid and caffeic acid. Fai et al. (2016) reported that coatings of fresh carrots with residual flavors from orange, watermelon, lettuce, and passion fruit peels inhibited microbial and yeast growth. Moreover, incorporating plant-based pigments can create indicator films to monitor freshness. Toro-Márquez et al. (2018) produced pH-sensitive films using *Hibiscus sabdariffa* flower extract in a corn-starch matrix. Merino et al. (2022) developed highly stretchable biodegradable mulching films by plasticizing Polylactic Acid (PLA) with VW from spinach stems, tomato pomace, and cocoa shells, which increased the film's biodegradability by up to 38 wt % for PLA composites after 6 months. Growing consumer awareness and preference for organic bio-packaging have driven the use of bioplastics. However, bioplastics face challenges, including product lifespan, biodegradability, availability of virgin biomass, the high volume of agro-waste, intensive purification, and elevated production costs, which hinder their potential to replace traditional petroleum-based plastics. Consumer confusion over bioplastic identification compounds these issues; for instance, Bio-PET indicates a vegetable source but is neither biodegradable nor compostable. To enhance the feasibility of cellulose/hemicellulose/lignin-based bioplastics, novel extraction and purification methods are needed to reduce costs. Significant efforts are underway to develop bacterial strains and improve fermentation and recovery processes to lower production expenses. Key prospects for making bioplastic production more industrially viable include utilizing less expensive substrates, optimizing microbial growth strategies, and simplifying downstream processing, all of which are crucial for reducing production costs.

5 Limitations in utilization of VW

The growing focus on sustainability has led to the exploration of vegetable waste as a valuable resource for various food and non-food applications. However, several challenges hinder its effective utilization. The primary challenge in utilizing VW is the risk of contamination, as its products may carry pesticide residues, heavy metals, or microbes, requiring proper processing to ensure safety (Hasan et al., 2024). However, extensive processing may lead to changes in color, odor, texture, odd mouth-feel affecting the overall acceptability and sensory quality. Furthermore, toxins (such as aflatoxins, mycotoxins, and fumonisins) and naturally occurring anti-nutritional compounds (including saponins, solasodine, tannins, phytates, oxalates, and alkaloids) present in VW pose significant safety concerns due to their ubiquity and potential adverse effects on human health (Kumar et al., 2022). The secondary feed stock used for volarisation often struggles to compete with traditional food production because it is perceived inferior, sparking consumer controversy. Processing companies can volarise food waste and its products by integrating them into innovative industrial products (Capanoglu et al., 2022). But strict food safety regulations, extensive testing of these products, strict quality standards, consistent availability of VW (Including logistical, seasonal, technical, economical), processing factors (Such as moisture, pH, C/N ratio, and bulking agents, processing steps and designs) often complicates industrial adoption (Jones et al., 2021). The inadequate characterization and segregation of VW from overall municipal waste severely hampers the effective utilization of VW in developing countries (Sarkar et al., 2023). To effectively transform VW research into real-world applications—such as converting it into viable biobased feedstock for non-food uses—it is essential to achieve high efficiency, maintain superior product quality, and ensure cost-effectiveness. Application of VW in non-food sectors—such as its conversion into energy—is still in its infancy, it is crucial to benchmark these emerging technologies against fossil-based alternatives. Comprehensive evaluations using tools like life cycle assessment (LCA), life cycle costing (LCC), and social life cycle assessment (s-LCA) are essential to fully capture their economic, environmental, and social impacts (Mak et al., 2020). High costs, financial constraints, and a lack of a robust demand-pull effect are hindering the commercialization of these technologies. Several key challenges affect VW management and the development of bio-based products. Kretschmer et al. (2013) identified five critical factors for FW management, which also apply to VW management. First, the variability in waste quality and volume makes it difficult to ensure a consistent and uniform feedstock supply. Second, the collection process lacks coordination due to the diverse sources of food waste. Third, inadequate infrastructure and limited storage facilities pose significant challenges, as food waste decomposes rapidly. Additionally, the demand for bio-based products is highly dependent on policy implementation, requiring strong legislative support and active public engagement. Lastly, limited public awareness remains a barrier to increasing demand for bio-based products, as they are often more expensive than conventional alternatives. Future research could begin with the fundamental aspects, such as collecting precise data on the quantity of specific vegetable waste generated, analyzing consumer behavior toward transformed or integrated products, and assessing the nutritional quality of compounds present in food waste.

6 SDG realization

Food loss and waste are extremely ineffective uses of resources from an environmental point of view. Research conducted by the UN Food and Agriculture Organization (FAO) estimates that greenhouse gas emissions from food loss and waste measures roughly up to 3.3 gigatonnes (Lipinski, 2015).

With the globe is in urgent need of a significantly sustainable strategy for future, the United Nations member states initiated an idea of forming goals to face those challenges and formally established in the name of Sustainable Development Goals in 2015, spanning the years 2016 to 2030 (Fukuda-Parr, 2019). These Sustainable Development Goals (SDGs), also referred to as the Global Goals, are a set of objectives established by international agreement to protect the planet's habitability in all its aspects, combat poverty, and guarantee that people live in peace and prosperity both now and in the future (Morton et al., 2017). Basically, it was started with 17 SDGs with 169 targets. Environmental preservation, social inclusion, and economic prosperity are the three aspects of sustainable development that are covered by these goals (Manzoor et al., 2024). Among all the SDGs, SDG 2, SDG 12, SDG 13 and SDG 14 are related to mitigation of food waste and poverty while SDG 2 aims to eradicate hunger, SDG 12 promotes sustainable consumption and production (SCP) patterns, SDG 13 combats climate change, and SDG 14 conserves marine ecosystems. To support the SDGs, the US Department of Agriculture and the US Environmental Protection Agency set the ambitious target of halving food waste in the US by the year 2030. The United Kingdom reduced food waste by 21% in just 5 years, while Denmark accomplished a remarkable 25% reduction in the same period (Lipinski, 2015).

Implementing circular economy solutions to reduce vegetable waste and promote sustainable consumption can accelerate progress on SDGs 2 and 12 (Mokrane et al., 2023). Our objective to utilize vegetable waste for producing bioactive products, biofertilizers, biofilms, and biofuels aligns with these goals. Consuming by-products from vegetable waste, which retain similar nutritional value, has been linked to a lower risk of stroke, heart disease, and various cancers. For example, vegetable by-product flours are high in fiber and contain beneficial bioactive substances like carotenoids and phenolic acids (Acosta-Estrada et al., 2014). This aligns with the goal of promoting overall well-being through preventive healthcare and healthy lifestyle choices, contributing to SDG 2. Food loss and waste lead to the indirect loss of vital resources such as land, water, and energy, while exacerbating environmental issues by releasing toxic greenhouse gasses during decomposition in landfills. Reducing food loss and waste supports Goal 12.3 on sustainable production and consumption (Augustin et al., 2020). Goal 12.5 focuses on significantly reducing waste generation through prevention, recycling, and reuse (UNEP, 2021). The dumping of vegetable waste contributes to greenhouse gas emissions, with increased vegetable production leading to greater waste accumulation, further impacting the climate and disrupting natural cycles. Achieving SDG 13 requires minimizing waste production and repurposing materials to create valuable by-products, such as food additives and essential oils, to combat malnutrition. Although the marine ecosystem is larger than terrestrial ecosystems, waste release into oceans disrupts marine life and ecosystems. Thus, repurposing vegetable waste for by-product production can help achieve Sustainable Development Goal 14.

7 Conclusion

Agricultural production was once well-balanced with waste management. However, with the increasing global population, changing lifestyles, seasonal production, and globalization, there has been a shift toward higher consumption of processed products. This shift has resulted in the generation of significant waste during the processing, grading, and sorting of agricultural products worsened by market fluctuations. Given the presence of bioactive compounds in these residues, there is an opportunity to create value-added products from existing VW for applications in medicine, food, industry, and technology. Adopting novel and sustainable extraction techniques that are cost-effective and feasible for commercialization is crucial. Educating consumers about reducing food waste and promoting the potential uses of vegetable processing waste can stimulate demand for these products. Future initiatives should highlight the environmental and economic benefits of waste valorisation through targeted marketing campaigns and educational programs. Embracing concepts such as circular economy, waste-to-wealth, and waste-to-energy offers sustainable solutions for creating a healthier planet and society. Furthermore, integrating VW into innovations like urban farming and vertical agriculture can capitalize on its potential to benefit the environment, economy, and society at large.

Author contributions

SB: Conceptualization, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. IC: Supervision, Writing – review & editing. RJ: Conceptualization, Methodology, Writing – review & editing. KR: Methodology, Validation, Writing – review & editing. AG: Conceptualization, Investigation, Methodology, Writing – review & editing. GK: Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abiy, T., and Tesfaye, A. (2019). Evaluation and optimization of agro-industrial wastes for conidial production of *Metarhizium anisopliae* isolates under solid state fermentation. *Momona Ethiop. J. Sci.* 11, 209–228. doi: 10.4314/mejs.v11i2.3

Acosta-Estrada, B. A., Guti'Errez-Uribe, J. A., and Serna-Saldívar, S. O. (2014). Bound phenolics in foods, a review. *Food Chem.* 152, 46–55. doi: 10.1016/j.foodchem.2013.11.093

Adugna, G., Bogale, B. M., and Nigussie, H. (2024). Effect of supplementing concentrate mixture with field pea hull on yearling ram lambs of local sheep: nutrient intake, linear body measurements, and changes in body weight. *Ethiop. Vet. J.* 28, 88–104. doi: 10.4314/evj.v28i1.6

Afinjuomo, F., Abdella, S., Youssef, S. H., Song, Y., and Garg, S. (2021). Inulin and its application in drug delivery. *Pharmaceuticals* 14:855. doi: 10.3390/ph14090855

Ahmad, G., and Khan, A. A. (2019). Pumpkin: horticultural importance and its roles in various forms; a review. *Int. J. Hortic. Agric.* 4, 1–6. doi: 10.15226/2572-3154/4/1/00124

Aisara, J., Wongputtisin, P., Deejing, S., Maneewong, C., Unban, K., Khanongnuch, C., et al. (2021). Potential of inulin-fructooligosaccharides extract produced from red onion (*Allium cepa* var. *viviparum* (Metz) Mansf.) as an alternative prebiotic product. *Plan. Theory* 10:2401. doi: 10.3390/plants10112401

Anupong, W., Jutamas, K., On-Uma, R., Sabour, A., Alshiekheid, M., Karuppusamy, I., et al. (2022). Sustainable bioremediation approach to treat the sago industry effluents and evaluate the possibility of yielded biomass as a single cell protein (SCP) using cyanide tolerant *Streptomyces tritici* D5. *Chemosphere* 304:135248:135248. doi: 10.1016/j.chemosphere.2022.135248

Asioli, D., Aschemann-Witzel, J., Caputo, V., Vecchio, R., Annunziata, A., Næs, T., et al. (2017). Making sense of the "clean label" trends: a review of consumer food choice behavior and discussion of industry implications. *Food Res. Int.* 99, 58–71. doi: 10.1016/j.foodres.2017.07.022

Athikomkulchai, S., Tunit, P., Tadtong, S., Jantrawut, P., Sommano, S. R., and Chittasupho, C. (2020). *Moringa oleifera* seed oil formulation physical stability and chemical constituents for enhancing skin hydration and antioxidant activity. *Cosmetics* 8:2. doi: 10.3390/cosmetics8010002

Augustin, M. A., Sanguansri, L., Fox, E. M., Cobiac, L., and Cole, M. B. (2020). Recovery of wasted fruit and vegetables for improving sustainable diets. *Trends Food Sci. Technol.* 95, 75–85. doi: 10.1016/j.tifs.2019.11.010

Ayilara, M. S., Adeleke, B. S., Akinola, S. A., Fayose, C. A., Adeyemi, U. T., Gbadegesin, L. A., et al. (2023). Biopesticides as a promising alternative to synthetic pesticides: a case for microbial pesticides, phytopesticides, and nanobiopesticides. *Front. Microbiol.* 14:1040901. doi: 10.3389/fmicb.2023.1040901

Ayyat, M. S., Ayyat, A. M. N., Abdel-Rahman, M. S., and Al-Sagheer, A. A. (2024). Appraisal of leaf protein concentrate derived from sugar beet and carrot as a novel fish meal substitute for juvenile Nile tilapia (*Oreochromis niloticus*). *Anim. Feed Sci. Technol.* 307:115833. doi: 10.1016/j.anifeedsci.2023.115833

Badıllı, U., Mollarasouli, F., Bakirhan, N. K., Ozkan, Y., and Ozkan, S. A. (2020). Role of quantum dots in pharmaceutical and biomedical analysis, and its application in drug delivery. *TrAC Trends Anal. Chem.* 131:116013. doi: 10.1016/j.trac.2020.116013

Badr, S. E., Shaaban, M., Elkholy, Y. M., Helal, M. H., Hamza, A. S., Masoud, M. S., et al. (2011). Chemical composition and biological activity of ripe pumpkin fruits (*Cucurbita pepo* L.) cultivated in Egyptian habitats. *Nat. Prod. Res.* 25, 1524–1539. doi: 10.1080/14786410903312991

Bearth, A., Cousin, M. E., and Siegrist, M. (2014). The consumer's perception of artificial food additives: influences on acceptance, risk and benefit perceptions. *Food Qual. Prefer.* 38, 14–23. doi: 10.1016/j.foodqual.2014.05.008

Behera, S., and Gupta, N. (2015). Utilization of vegetable waste for biomass production of some wild edible mushroom cultures. *Trop. Plant Res.* 2, 5–9.

Benucci, I., Lombardelli, C., Mazzocchi, C., and Esti, M. (2022). Natural colorants from vegetable food waste: recovery, regulatory aspects, and stability—a review. *Compr. Rev. Food Sci. Food Saf.* 21, 2715–2737. doi: 10.1111/1541-4337.12951

Berglund, J., Mikkelsen, D., Flanagan, B. M., Dhital, S., Gaunitz, S., Henriksson, G., et al. (2020). Wood hemicelluloses exert distinct biomechanical contributions to cellulose fibrillar networks. *Nat. Commun.* 11:4692. doi: 10.1038/s41467-020-18390-z

Bernaś, E., and Jaworska, G. (2015). Use of onion extract to prevent enzymatic browning of frozen Agaricus bisporus mushrooms. *Int. J. Refriger.* 57, 257–264. doi: 10.1016/j.ijrefrig.2015.04.022

Bidura, I. G. N. G., Siti, N. W., Wibawa, A. A. P. P., Ariana, I. N. T., and Puspani, E. (2021). The effect of Carot leaves meal fermented in diets on egg production, yolk cholesterol and beta-carotene in yolk of hens. *Ann. Rom. Soc. Cell Biol.* 25, 18705–18711.

Bolan, N., Hoang, S. A., Beiyuan, J., Gupta, S., Hou, D., Karakoti, A., et al. (2022). Multifunctional applications of biochar beyond carbon storage. *Int. Mater. Rev.* 67, 150–200. doi: 10.1080/09506608.2021.1922047

Boonen, J., Veryser, L., Taevernier, L., Roche, N., Peremans, K., Burvenich, C., et al. (2014). Risk evaluation of impurities in topical excipients: the acetol case. *J. Pharm. Anal.* 4, 303–315. doi: 10.1016/j.jpha.2013.12.006

Burger, T. G., and Zhang, Y. (2019). Recent progress in the utilization of pea protein as an emulsifier for food applications. *Trends Food Sci. Technol.* 86, 25–33. doi: 10.1016/j.tifs.2019.02.007

Campos, D. A., Coscueta, E. R., Vilas-Boas, A. A., Silva, S., Teixeira, J. A., Pastrana, L. M., et al. (2020). Impact of functional flours from pineapple by-products on human intestinal microbiota. *J. Funct. Foods* 67:103830. doi: 10.1016/j.jff.2020.103830

Capanoglu, E., Nemli, E., and Tomas-Barberan, F. (2022). Novel approaches in the valorization of agricultural wastes and their applications. *J. Agric. Food Chem.* 70, 6787–6804. doi: 10.1021/acs.jafc.1c07104

Carbonaro, M., Maselli, P., and Nucara, A. (2015). Structural aspects of legume proteins and nutraceutical properties. *Food Res. Int.* 76, 19–30. doi: 10.1016/j.foodres.2014.11.007

Carpena, M., Nuñez-Estevez, B., Soria-Lopez, A., Garcia-Oliveira, P., and Prieto, M. A. (2021). Essential oils and their application on active packaging systems: a review. *Resources* 10:7. doi: 10.3390/resources10010007

Caseiro, M., Ascenso, A., Costa, A., Creagh-Flynn, J., Johnson, M., and Simões, S. (2020). Lycopene in human health. *LWT* 127:109323:109323. doi: 10.1016/j.lwt.2020.109323

Chaari, M., Elhadef, K., Akermi, S., Tounsi, L., Hlima, H. B., Ennouri, M., et al. (2024). Development of a novel colorimetric pH-indicator film based on CMC/flaxseed gum/betacyanin from beetroot peels: a powerful tool to monitor the beef meat freshness. *Sustain. Chem. Pharm.* 39:101543. doi: 10.1016/j.scp.2024.101543

Chae, M. R., Kang, S. J., Lee, K. P., Choi, B. R., Kim, H. K., Park, J. K., et al. (2017). Onion (*Allium cepa* L.) peel extract (OPE) regulates human sperm motility via protein kinase C-mediated activation of the human voltage-gated proton channel. *Andrology* 5, 979–989. doi: 10.1111/andr.12406

Cheng, Y., Zhai, X., Wu, Y., Li, C., Zhang, R., Sun, C., et al. (2023). Effects of natural wax types on the physicochemical properties of starch/gelatin edible films fabricated by extrusion blowing. *Food Chem.* 401:134081. doi: 10.1016/j.foodchem.2022.134081

Chiboub, W., Sassi, A. B., Amina, C. M. H., Souilem, F., El Ayeb, A., Djlassi, B., et al. (2019). Valorization of the green waste from two varieties of fennel and carrot cultivated in Tunisia by identification of the phytochemical profile and evaluation of the antimicrobial activities of their essential oils. *Chem. Biodivers.* 16:e1800546. doi: 10.1002/cbdv.201800546

Chong, B., Kong, G., Shankar, K., Chew, H. S. J., Lin, C., Goh, R., et al. (2023). The global syndemic of metabolic diseases in the young adult population: a consortium of trends and projections from the global burden of disease 2000–2019. *Metabolism* 141:155402. doi: 10.1016/j.metabol.2023.155402

Choudhury, A., Sarma, S., Sarkar, S., Kumari, M., and Dey, B. K. (2022). Polysaccharides obtained from vegetables: an effective source of alternative excipient. *J. Pharmacopuncture* 25, 317–325. doi: 10.3831/KPI.2022.25.4.317

Claros Cuadrado, J. L., Pinillos, E. O., Tito, R., Mirones, C. S., and Gamarra Mendoza, N. N. (2019). Insecticidal properties of capsaicinoids and glucosinolates extracted from Capsicum Chinense and *Tropaeolum tuberosum*. *Insects* 10:132. doi: 10.3390/insects10050132

Collins, E. J., Bowyer, C., Tsouza, A., and Chopra, M. (2022). Tomatoes: an extensive review of the associated health impacts of tomatoes and factors that can affect their cultivation. *Biology* 11:239. doi: 10.3390/biology11020239

Čolović, R., Puvača, N., Cheli, F., Avantaggiato, G., Greco, D., Đuragić, O., et al. (2019). Decontamination of mycotoxin-contaminated feedstuffs and compound feed. *Toxins* 11:617. doi: 10.3390/toxins11110617

Dantas, T. L., Alonso Buriti, F. C., and Florentino, E. R. (2021). Okra (*Abelmoschus esculentus* L.) as a potential functional food source of mucilage and bioactive compounds with technological applications and health benefits. *Plan. Theory* 10:1683. doi: 10.3390/plants10081683

Dastidar, D. G., Mukherjee, P., Ghosh, D., and Banerjee, D. (2021). Carbon quantum dots prepared from onion extract as fluorescence turn-on probes for selective estimation of Zn2+ in blood plasma. *Colloids Surf. A Physicochem. Eng. Asp.* 611:125781. doi: 10.1016/j.colsurfa.2020.125781

Devi, D., Kumar, S., and Mukherjee, A. (2024). Onion peel extract as milk freshness indicator in biopolymer-based intelligent packaging films. *Food and Humanity.* 2, 100223. doi: 10.1016/j.foohum.2023.100223

Dinç, S. (2016). A simple and green extraction of carbon dots from sugar beet molasses: biosensor applications. *Sugar Ind.* 141, 109323, 109323–109564. doi: 10.36961/si17741

Dos Santos Escobar, O., de Azevedo, C. F., Swarowsky, A., Adebayo, M. A., Netto, M. S., and Machado, F. M. (2021). Utilization of different parts of *Moringa oleifera* lam. Seeds as biosorbents to remove acid blue 9 synthetic dye. *J. Environ. Chem. Eng.* 9:105553:105553. doi: 10.1016/j.jece.2021.105553

Ducrocq, M., Boire, A., Anton, M., Micard, V., and Morel, M. H. (2020). Rubisco: a promising plant protein to enrich wheat-based food without impairing dough viscoelasticity and protein polymerisation. *Food Hydrocoll.* 109:106101. doi: 10.1016/j.foodhyd.2020.106101

Ebrahimi, N., Viaene, N., Vandecasteele, B., D'Hose, T., Debode, J., Cremelie, P., et al. (2016). Traditional and new soil amendments reduce survival and reproduction of potato cyst nematodes, except for biochar. *Appl. Soil Ecol.* 107, 191–204. doi: 10.1016/j.apsoil.2016.06.006

Edussuriya, R., Rajapaksha, A. U., Jayasinghe, C., Pathirana, C., and Vithanage, M. (2023). Influence of biochar on growth performances, yield of root and tuber crops and controlling plant-parasitic nematodes. *Biochar* 5:68. doi: 10.1007/s42773-023-00261-7

EMA. (2009). *ICH topic Q3C (R4) impurities: Guideline for residual solvents step 5, CPMP/ICH/283/95*. Available online at: https://www.ema.europa.eu/docs/en_GB/document_library/Scientific_guideline/2009/09/WC500002674.pdf.

Esparza, I., Jiménez-Moreno, N., Bimbela, F., Ancín-Azpilicueta, C., and Gandía, L. M. (2020). Fruit and vegetable waste management: conventional and emerging approaches. *J. Environ. Manag.* 265:110510. doi: 10.1016/j.jenvman.2020.110510

Fadlilla, T., Budiastuti, M. S., and Rosariastuti, M. R. (2023). Potential of fruit and vegetable waste as eco-enzyme fertilizer for plants. *J. Penelit. Pendidik. IPA* 9, 2191–2200. doi: 10.29303/jppipa.v9i4.3010

Fai, A. E. C., de Souza, M. R. A., de Barros, S. T., Bruno, N. V., Ferreira, M. S. L., and de Andrade Gonçalves, É. C. B. (2016). Development and evaluation of biodegradable films and coatings obtained from fruit and vegetable residues applied to fresh-cut carrot (*Daucus* carota L.). *Postharvest Biol. Technol.* 112, 194–204. doi: 10.1016/j.postharvbio.2015.09.021

FAO (2017). *The future of food and agriculture—Trends and challenges*. Rome, Italy: Food and Agriculture Organization.

FAO (2019). *The state of food and agriculture 2019: Moving forward on food loss and waste reduction*. Rome, Italy: Food and Agriculture Organization.

Firrman, J., Narrowe, A., Liu, L., Mahalak, K., Lemons, J., Van den Abbeele, P., et al. (2024). Tomato seed extract promotes health of the gut microbiota and demonstrates a potential new way to valorize tomato waste. *PLoS One* 19:e0301381. doi: 10.1371/journal.pone.0301381

Foti, C., Damiani, E., Zambonin, C. G., Cassano, N., Nettis, E., Ferrannini, A., et al. (2012). Urticaria and angioedema to rubisco allergen in spinach and tomato. *Ann. Allergy Asthma Immunol.* 108, 60–61. doi: 10.1016/j.anai.2011.09.011

Fukuda-Parr, S. (2019). Keeping out extreme inequality from the SDG agenda – the politics of indicators. *Glob. Policy* 10, 61–69. doi: 10.1111/1758-5899.12602

Ghosh, P. R., Fawcett, D., Sharma, S. B., and Poinern, G. E. (2017). Production of high-value nanoparticles via biogenic processes using aquacultural and horticultural food waste. *Materials* 10:852. doi: 10.3390/ma10080852

Ghosh, S., Chatterjee, P. N., Bera, S., and Saha, M. (2023). Effect of supplementing Azolla and empty pea pod on growth performance, blood biochemical metabolites and meat quality in white Pekin ducks. *Indian J. Anim. Sci.* 93, 1010–1014. doi: 10.56093/ijans.v93i10.134588

Girotto, F., and Piazza, L. (2022). Food waste bioconversion into new food: a mini-review on nutrients circularity in the production of mushrooms, microalgae and insects. *Waste Manag. Res.* 40, 47–53. doi: 10.1177/0734242X211038189

Goswami, C., Pawase, P. A., Shams, R., Pandey, V. K., Tripathi, A., Rustagi, S., et al. (2024). A conceptual review on classification, extraction, bioactive potential and role of phytochemicals in human health. *Futur. Foods* 9:100313. doi: 10.1016/j.fufo.2024.100313

Grácio, M., Oliveira, S., Lima, A., and Ferreira, R. B. (2023). RuBisCO as a protein source for potential food applications: a review. *Food Chem.* 419:135993. doi: 10.1016/j.foodchem.2023.135993

Gunders, D., and Bloom, J. (2017). *Wasted: how America is losing up to 40 percent of its food from farm to fork to landfill*. New York: Natural Resources Defense Council, 1–26.

Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., and Meybeck, A. (2011). *Global food losses and food waste: Extent, Causes and Prevention*. Rome: FAO.

Hadidi, M., Boostani, S., and Jafari, S. M. (2022). Pea proteins as emerging biopolymers for the emulsification and encapsulation of food bioactives. *Food Hydrocoll.* 126:107474. doi: 10.1016/j.foodhyd.2021.107474

Hajhashemi, V., Rajabi, P., and Mardani, M. (2019). Beneficial effects of pumpkin seed oil as a topical hair growth promoting agent in a mice model. *Avicenna J. Phytomed.* 9, 499–504. doi: 10.22038/AJP.2019.13463

Han, S., Seo, K. H., Lee, H. G., and Kim, H. (2023). Effect of *Cucumis melo* L. peel extract supplemented postbiotics on reprograming gut microbiota and sarcopenia in hindlimb-immobilized mice. *Food Res. Int.* 173:113476. doi: 10.1016/j.foodres.2023.113476

Hasan, M. M., Islam, M. R., Haque, A. R., Kabir, M. R., Khushe, K. J., and Hasan, S. K. (2024). Trends and challenges of fruit by-products utilization: insights into safety, sensory, and benefits of the use for the development of innovative healthy food: a review. *Bioresour. Bioprocess.* 11:10. doi: 10.1186/s40643-023-00722-8

Hirata, H., Sonoda, S., Agui, S., Yoshida, M., Ohinata, K., and Yoshikawa, M. (2007). Rubiscolin-6, a delta opioid peptide derived from spinach rubisco, has anxiolytic effect via activating sigma1 and dopamine D1 receptors. *Peptides* 28, 1998–2003. doi: 10.1016/j.peptides.2007.07.024

Hu, W. S., Nam, D. M., Choi, J. Y., Kim, J. S., and Koo, O. K. (2019). Anti-attachment, anti-biofilm, and antioxidant properties of Brassicaceae extracts on Escherichia coli O157:H7. *Food Sci Biotechnol.* 28, 1881–1890. doi: 10.1007/s10068-019-00621-9

Hufnagl, K., and Jensen-Jarolim, E. (2019). Does a carrot a day keep the allergy away? *Immunol. Lett.* 206, 54–58. doi: 10.1016/j.imlet.2018.10.009

Islam, F., Amer Ali, Y., Imran, A., Afzaal, M., Zahra, S. M., Fatima, M., et al. (2023). Vegetable proteins as encapsulating agents: recent updates and future perspectives. *Food Sci. Nutr.* 11, 1705–1717. doi: 10.1002/fsn3.3234

Issa, A. T., Schimmel, K. A., Worku, M., Shahbazi, A., Ibrahim, S. A., and Tahergorabi, R. (2018). Sweet potato starch-based nanocomposites: development, characterization, and biodegradability. *Starch Stärke* 70:1700273. doi: 10.1002/star.201700273

Jadhav, P., Sonne, M., Kadam, A., Patil, S., Dahigaonkar, K., and Oberoi, J. K. (2018). Formulation of cost effective alternative bacterial culture media using fruit and vegetables waste. *Int. J. Curr. Res. Rev.* 10:6. doi: 10.7324/IJCRR.2018.1022

Jeong, S. G., Kim, H. M., Lee, M., Yang, J. E., and Park, H. W. (2023). Use of vegetable waste as a culture medium ingredient improves the antimicrobial and immunomodulatory activities of *Lactiplantibacillus plantarum* WiKim0125 isolated from kimchi. *J. Microbiol. Biotechnol.* 33, 75–82. doi: 10.4014/jmb.2210.10049

Jhanani, G. K., AlSalhi, M. S., Naveena, T., and Shanmuganathan, R. (2024). As assessment of shelf life increasing competence of pectin (zucchini) based edible coating on tomatoes. *Environ. Res.* 258:119368. doi: 10.1016/j.envres.2024.119368

Jones, S. L., Gibson, K. E., and Ricke, S. C. (2021). Critical factors and emerging opportunities in food waste utilization and treatment technologies. *Front. Sustain. Food Syst.* 5:781537. doi: 10.3389/fsufs.2021.781537

Ju, J., Xie, Y., Guo, Y., Cheng, Y., Qian, H., and Yao, W. (2019). Application of edible coating with essential oil in food preservation. *Crit. Rev. Food Sci. Nutr.* 59, 2467–2480. doi: 10.1080/10408398.2018.1456402

Kakabouki, I., Efthimiadou, A., Folina, A., Zisi, C., and Karydogianni, S. (2020). Effect of different tomato pomace compost as organic fertilizer in sweet maize crop. *Commun. Soil Sci. Plant Anal.* 51, 2858–2872. doi: 10.1080/00103624.2020.1853148

Keske, C., Godfrey, T., Hoag, D. L., and Abedin, J. (2020). Economic feasibility of biochar and agriculture coproduction from Canadian black spruce forest. *Food Energy Secur.* 9:e188. doi: 10.1002/fes3.188

Khan, M. K. I., Asif, M., Razzaq, Z. U., Nazir, A., and Maan, A. A. (2022). Sustainable food industrial waste management through single cell protein production and characterization of protein enriched bread. *Food Biosci.* 46:101406. doi: 10.1016/j.fbio.2021.101406

Kian, L. K., Saba, N., Jawaid, M., and Fouad, H. (2020). Characterization of microcrystalline cellulose extracted from olive fiber. *Int. J. Biol. Macromol.* 156, 347–353. doi: 10.1016/j.ijbiomac.2020.04.015

Kim, S. J., Chandrasekar, B., Rea, A. C., Danhof, L., Zemelis-Durfee, S., Thrower, N., et al. (2020). The synthesis of xyloglucan, an abundant plant cell wall polysaccharide, requires CSLC function. *Proc. Natl. Acad. Sci.* 117, 20316–20324. doi: 10.1073/pnas.2007245117

Kitson-Hytey, M., Fei-Baffoe, B., Sackey, L. N., and Miezah, K. (2024). Production of bioethanol from plantain and yam peels using aspergillus Niger and *Saccharomyces cerevisiae*. *Biomass Convers. Biorefinery* 14, 9087–9095. doi: 10.1007/s13399-022-03352-w

Kobbi, S., Balti, R., Bougatef, A., Le Flem, G., Firdaous, L., Bigan, M., et al. (2015). Antibacterial activity of novel peptides isolated from protein hydrolysates of RuBisCO purified from green juice alfalfa. *J. Funct. Foods* 18, 703–713. doi: 10.1016/j.jff.2015.09.007

Kocić-Tanackov, S., Dimić, G., Mojović, L., Gvozdanović-Varga, J., Djukić-Vuković, A., Tomović, V., et al. (2017). Antifungal activity of the onion (*Allium cepa* L.) essential oil against aspergillus, *Fusarium* and Penicillium species isolated from food. *J. Food Process. Preserv.* 41:e13050. doi: 10.1111/jfpp.13050

Kovarovič, J., Bystrická, J., Vollmannová, A., Tóth, T., and Brindza, J. (2019). Biologically valuable substances in garlic (*Allium sativum* L.)–a review. *J. Cent. Eur. Agric.* 20, 292–304. doi: 10.5513/JCEA01/20.1.2304

Kretschmer, B., Smith, C., Watkins, E., Allen, B., Buckwell, A., Desbarats, J., et al. (2013). *Recycling agricultural, Forestry & Food Wastes and residues for sustainable bioenergy and biomaterials (part of the Project 'Technology options for feeding 10 billion People')*. https://ieep.eu/uploads/articles/attachments/a82c7cd8-ed6c-4b0b-89ba4d1a01e403f/Study_5_WR_12Sep13_15_slide_version.Pdf?V=63664509820 (Assessed March 13, 2025).

Krishnaiah, P., Atchudan, R., Perumal, S., Gangadaran, P., Manoj, D., Ahn, B. C., et al. (2024). Multifunctional carbon dots originated from waste garlic peel for rapid sensing of heavy metals and fluorescent imaging of 2D and 3D spheroids cultured fibroblast cells. *Spectrochim. Acta A Mol. Biomol. Spectrosc.* 304:123422. doi: 10.1016/j.saa.2023.123422

Kumar, A., Bhattacharya, T., Shaikh, W. A., Roy, A., Chakraborty, S., Vithanage, M., et al. (2023). Multifaceted applications of biochar in environmental management: a bibliometric profile. *Biochar* 5:11. doi: 10.1007/s42773-023-00207-z

Kumar, M., Barbhai, M. D., Hasan, M., Punia, S., Dhumal, S., Radha, R., et al. (2022). Onion (*Allium cepa* L.) peels: a review on bioactive compounds and biomedical activities. *Biomed. Pharmacother.* 146:112498. doi: 10.1016/j.biopha.2021.112498

Kumar, S. S., Manoj, P., Shetty, N. P., Prakash, M., and Giridhar, P. (2015). Characterization of major betalain pigments -gomphrenin, betanin and isobetanin from Basella rubra L. fruit and evaluation of efficacy as a natural colourant in product (ice cream) development. *J. Food Sci. Technol.* 52, 4994–5002. doi: 10.1007/s13197-014-1527-z

Kurra, P., Narra, K., Orfali, R., Puttugunta, S. B., Khan, S. A., Meenakshi, D. U., et al. (2022). Studies on jackfruit-okra mucilage-based curcumin Mucoadhesive tablet for Colon targeted delivery. *Front. Pharmacol.* 13:902207. doi: 10.3389/fphar.2022.902207

Kushwaha, R., Kumar, V., Vyas, G., and Kaur, J. (2018). Optimization of different variable foreco-friendly extraction of betalains and phytochemicals from beetroot pomace. *Waste Biomass Valorization* 9, 1485–1494. doi: 10.1007/s12649-017-9953-6

Lien, N. P. H., Chi, T. D., Harada, H., and Fujii, S. (2018). Biomethane potential (BMP) of arrowroot powder processing waste and effect of alkaline pre-treatment. *Vietnam J. Sci. Technol.* 56, 171–177. doi: 10.15625/2525-2518/56/2C/13045

Liese, H. W., Valkenburg, T. A. A., America, A. H. P., Scholten, E., and Bruins, M. E. (2023). Toxin removal during protein extraction from tomato leaves. *Innov. Food Sci. Emerg. Technol.* 88:103454. doi: 10.1016/j.ifset.2023.103454

Li, P. (2022). Analysis of vegetable waste pollution risk and resource potential based on geographical information system and remote sensing. *J Sens* 2022, 1–12. doi: 10.1155/2022/3871406

Lipinski, B. (2015). *What's food loss and waste got to do with sustainable development? A lot, Actually*. World Resources Institute. Available online at: https://www.wri.org/insights/whats-food-loss-and-waste-got-do-sustainable-development-lot-actually.

Liu, F., Ren, J., Yang, Q., Zhang, Q., Zhang, Y., Xiao, X., et al. (2024). Improving water resistance and mechanical properties of starch-based films by incorporating microcrystalline cellulose in a dynamic network structure. *Int. J. Biol. Macromol.* 260:129404. doi: 10.1016/j.ijbiomac.2024.129404

Lombardelli, C., Benucci, I., Mazzocchi, C., and Esti, M. (2021). A novel process for the recovery of betalains from unsold red beets by low-temperature enzyme-assisted extraction. *Food Secur.* 10:236. doi: 10.3390/foods10020236

Lombardelli, C., Benucci, I., Mazzocchi, C., and Esti, M. (2022). Green enzymatic recovery of functional bioactive compounds from unsold vegetables: storability and potential health benefits. *Appl. Sci.* 12:12249. doi: 10.3390/app122312249

Lombardelli, C., Liburdi, K., Benucci, I., and Esti, M. (2020). Tailored and synergistic enzyme-assisted extraction of carotenoid-containing chromoplasts from tomatoes. *Food Bioprod. Process.* 121, 43–53. doi: 10.1016/j.fbp.2020.01.014

Majumder, R., Pal, T., Basumallick, A., and Mukhopadhyay, C. D. (2021). Functionalized carbon nano onion as a novel drug delivery system for brain targeting. *J. Drug Deliv. Sci. Technol.* 63:102414. doi: 10.1016/j.jddst.2021.102414

Mak, T. M., Xiong, X., Tsang, D. C., Iris, K. M., and Poon, C. S. (2020). Sustainable food waste management towards circular bioeconomy: policy review, limitations and opportunities. *Bioresour. Technol.* 297:122497. doi: 10.1016/j.biortech.2019.122497

Mandal, S., Pu, S., Adhikari, S., Ma, H., Kim, D. H., Bai, Y., et al. (2021). Progress and future prospects in biochar composites: application and reflection in the soil environment. *Crit. Rev. Environ. Sci. Technol.* 51, 219–271. doi: 10.1080/10643389.2020.1713030

Manzoor, S., Fayaz, U., Dar, A. H., Dash, K. K., Shams, R., Bashir, I., et al. (2024). Sustainable development goals through reducing food loss and food waste: a comprehensive review. *Future Foods* 9:100362. doi: 10.1016/j.fufo.2024.100362

Marrufo, T., Nazzaro, F., Mancini, E., Fratianni, F., Coppola, R., De Martino, L., et al. (2013). Chemical composition and biological activity of the essential oil from leaves of *Moringa oleifera* Lam. Cultivated in Mozambique. *Molecules* 18, 10989–11000. doi: 10.3390/molecules180910989

Martínez-Inda, B., Simón, O., Jiménez-Moreno, N., Esparza, I., Moler, J. A., Caballero, P., et al. (2023). Vegetable waste extracts as enhancers of baculovirus infections. *Ann. Agric. Sci.* 68, 96–107. doi: 10.1016/j.aoas.2023.11.001

Mazzocchi, C., Benucci, I., Lombardelli, C., and Esti, M. (2023). Enzyme-Assisted Extraction for the Recovery of Food-Grade Chlorophyll-Based Green Colorant. *Foods.* 12, 3440. doi: 10.3390/foods12183440

Merino, D., Zych, A., and Athanassiou, A. (2022). Biodegradable and biobased mulch films: highly stretchable PLA composites with different industrial vegetable waste. *ACS Appl. Mater. Interfaces* 14, 46920–46931. doi: 10.1021/acsami.2c10965

Messias, M. A., Ferreira, S. M., Tavares, L., and Santos, L. (2023). A comparative study between onion Peel extracts, free and complexed with β-cyclodextrin, as a natural UV filter to cosmetic formulations. *Int. J. Mol. Sci.* 24:15854. doi: 10.3390/ijms242115854

Mnayer, D., Fabiano-Tixier, A. S., Petitcolas, E., Hamieh, T., Nehme, N., Ferrant, C., et al. (2014). Chemical composition, antibacterial and antioxidant activities of six essentials oils from the Alliaceae family. *Molecules* 19, 20034–20053. doi: 10.3390/molecules191220034

Mokrane, S., Buonocore, E., Capone, R., and Franzese, P. P. (2023). Exploring the global scientific literature on food waste and loss. *Sustain. For.* 15:4757. doi: 10.3390/su15064757

Molaei, M. J. (2020). Principles, mechanisms, and application of carbon quantum dots in sensors: a review. *Anal. Methods* 12, 1266–1287. doi: 10.1039/C9AY02696G

Monte-Filho, S. S., Andrade, S. I., Lima, M. B., and Araujo, M. C. (2019). Synthesis of highly fluorescent carbon dots from lemon and onion juices for determination of riboflavin in multivitamin/mineral supplements. *J. Pharm. Anal.* 9, 209–216. doi: 10.1016/j.jpha.2019.02.003

Monteiro, S. A., Carreira, A., Freitas, R., Pinheiro, A. M., and Ferreira, R. B. (2015). A nontoxic polypeptide oligomer with a fungicide potency under agricultural conditions which is equal or greater than that of their chemical counterparts. *PLoS One* 10:e0122095. doi: 10.1371/journal.pone.0122095

Morton, S., Pencheon, D., and Squires, N. (2017). Sustainable development goals (SDGs), and their implementation a national global framework for health, development and equity needs a systems approach at every level. *Br. Med. Bull.* 1–10, 1–10. doi: 10.1093/bmb/ldx031

Nogueira, G. F., Leme, B. D. O., Santos, G. R. S. D., Silva, J. V. D., Nascimento, P. B., Soares, C. T., et al. (2021). Edible films and coatings formulated with arrowroot starch as a non-conventional starch source for plums packaging. *Polysaccharides* 2, 373–386. doi: 10.3390/polysaccharides2020024

Novais, C., Molina, A. K., Abreu, R. M., Santo-Buelga, C., Ferreira, I. C., Pereira, C., et al. (2022). Natural food colorants and preservatives: a review, a demand, and a challenge. *J. Agric. Food Chem.* 70, 2789–2805. doi: 10.1021/acs.jafc.1c07533

Nowak, K., Wiater, A., Choma, A., Wiącek, D., Bieganowski, A., Siwulski, M., et al. (2019). Fungal (1→ 3)-α-d-glucans as a new kind of biosorbent for heavy metals. *Int. J. Biol. Macromol.* 137, 960–965. doi: 10.1016/j.ijbiomac.2019.07.036

Olubi, O. (2018). *Functional characteristics of egusi seed (Citrullus lanatus) hydrocolloid and oil in instant egusi soup*. (Doctoral dissertation, Cape Peninsula University of Technology). Available online at: http://hdl.handle.net/20.500.11838/2785.

Onoda, Y., Wright, I. J., Evans, J. R., Hikosaka, K., Kitajima, K., Niinemets, U., et al. (2017). Physiological and structural tradeoffs underlying the leaf economics spectrum. *New Phytol.* 214, 1447–1463. doi: 10.1111/nph.14496

Owusu, F. W. A., Boakye-Gyasi, M. E., Agbenorhevi, J. K., Bayor, M. T., and Ofori-Kwakye, K. (2021). Potential and comparative tablet disintegrant properties of pectin obtained from five okra genotypes in Ghana. *Scientifica* 2021:2902335. doi: 10.1155/2021/2902335

Oyom, W., Xu, H., Liu, Z., Long, H., Li, Y., Zhang, Z., et al. (2022). Effects of modified sweet potato starch edible coating incorporated with cumin essential oil on storage quality of 'early crisp'. *LWT* 153:112475. doi: 10.1016/j.lwt.2021.112475

Panda, S. K., Ray, R. C., Mishra, S. S., and Kayitesi, E. (2018). Microbial processing of fruit and vegetable wastes into potential biocommodities: a review. *Crit. Rev. Biotechnol.* 38, 1–16. doi: 10.1080/07388551.2017.1311295

Patel, S. (2013). Pumpkin (Cucurbita sp.) seeds as nutraceutic: a review on status quo and scopes. *Mediterr. J. Nutr. Metab.* 6, 183–189. doi: 10.3233/s12349-013-0131-5

Patelski, P., Berlowska, J., Dziugan, P., Pielech-Przybylska, K., Balcerek, M., Dziekonska, U., et al. (2015). Utilisation of sugar beet bagasse for the biosynthesis of yeast SCP. *J. Food Eng.* 167, 32–37. doi: 10.1016/j.jfoodeng.2015.03.031

Pearce, F. G., and Brunke, J. E. (2023). Is now the time for a Rubiscuit or Ruburger? Increased interest in rubisco as a food protein. *J. Exp. Bot.* 74, 627–637. doi: 10.1093/jxb/erac414

Peira, G., Bollani, L., Giachino, C., and Bonadonna, A. (2018). The management of unsold food in outdoor market areas: food operators' behaviour and attitudes. *Sustain. For.* 10:1180. doi: 10.3390/su10041180

Pereira, J. A., Berenguer, C. V., Andrade, C. F., and Câmara, J. S. (2022). Unveiling the bioactive potential of fresh fruit and vegetable waste in human health from a consumer perspective. *Appl. Sci.* 12:2747. doi: 10.3390/app12052747

Piirsalu, E., Moora, H., Väli, K., Värnik, R., Aro, K., and Lillemets, J. (2022). *The generation of food waste and food loss in the Estonian food supply chain*. Stockholm, Sweden: Stockholm Environment Institute.

Pradhan, S., Abdelaal, A. H., Mroue, K., Al-Ansari, T., Mackey, H. R., and McKay, G. (2020). Biochar from vegetable wastes: agro-environmental characterization. *Biochar* 2, 439–453. doi: 10.1007/s42773-020-00069-9

Qin, J., Li, R., Raes, J., Arumugam, M., Burgdorf, K. S., Manichanh, C., et al. (2010). A human gut microbial gene catalogue established by metagenomic sequencing. *Nature* 464, 59–65. doi: 10.1038/nature08821

Qin, Y. (2016). "Applications of advanced technologies in the development of functional medical textile materials" in *Woodhead publishing series in textiles, medical textile materials*. ed. Y. Qin (Amsterdam: Woodhead Publishing), 55–70.

Rahimah, S., Malinda, W., and Zaida, SukriN.Salma, J. K., and Tallei, T. E., et al. (2020). Betacyanin as Bioindicator Using Time-Temperature Integrator for Smart Packaging of Fresh Goat Milk. *Sci. World J.* 2020, e4303140. doi: 10.1155/2020/4303140

Raveendran, P. V., Aswathi, B. S., and Renuka, N. K. (2022). Arrowroot derived carbon dots: green synthesis and application as an efficient optical probe for fluoride ions. *Mater. Today Proc.* 51, 2417–2421. doi: 10.1016/j.matpr.2021.11.602

Rifna, E. J., Misra, N. N., and Dwivedi, M. (2023). Recent advances in extraction technologies for recovery of bioactive compounds derived from fruit and vegetable waste peels: a review. *Crit. Rev. Food Sci. Nutr.* 63, 719–752. doi: 10.1080/10408398.2021.1952923

Rodríguez-Martínez, B., Coelho, E., Gullón, B., Yáñez, R., and Domingues, L. (2023). Potato peels waste as a sustainable source for biotechnological production of biofuels: process optimization. *Waste Manag.* 155, 320–328. doi: 10.1016/j.wasman.2022.11.007

Roldán, E., Sanchez-Moreno, C., de Ancos, B., and Cano, M. P. (2008). Characterisation of onion (*Allium cepa* L.) by-products as food ingredients with antioxidant and antibrowning properties. *Food Chem.* 108, 907–916. doi: 10.1016/j.foodchem.2007.11.058

Saberi, B., Golding, J. B., Chockchaisawasdee, S., Scarlett, C. J., and Stathopoulos, C. E. (2018). Effect of biocomposite edible coatings based on pea starch and guar gum on nutritional quality of "Valencia" orange during storage. *Starch Stärke* 70:1700299. doi: 10.1002/star.201700299

Saidi, R., Hamdi, M., and Bouallagui, H. (2020). Hyperthermophilic hydrogen production in a simplified reaction medium containing onion wastes as a source of carbon and sulfur. *Environ. Sci. Pollut. Res.* 27, 17382–17392. doi: 10.1007/s11356-020-08270-w

Sánchez-Ponce, L., Díaz-de-Alba, M., Casanueva-Marenco, M. J., Gestoso-Rojas, J., Ortega-Iguña, M., Galindo-Riaño, M. D., et al. (2022). Potential use of low-cost Agri-food waste as biosorbents for the removal of cd (II), co (II), Ni (II) and Pb (II) from aqueous solutions. *Separations* 9:309. doi: 10.3390/separations9100309

Sardar, H., Anjum, M. A., Hussain, S., Ali, S., Shaheen, M. R., Ahsan, M., et al. (2022). Deciphering the role of moringa leaf powder as a supplement in the cotton waste substrate for the growth and nutrition of king oyster mushroom. *Sci. Hortic.* 293:e110694:110694. doi: 10.1016/j.scienta.2021.110694

Sarkar, A., Ghosh, D., and Das, A. (2023). *One health for sustainable development: an eco-social Design for a Climate Resilient Health Systems in the Sundarbans of bay of Bengal*. In one health for sustainable development: An eco-social Design for a Climate Resilient Health Systems in the Sundarbans of bay of Bengal. United Nations Research Institute for Social Development (UNRISD).

Sarker, A., Ahmmed, R., Ahsan, S. M., Rana, J., Ghosh, M. K., and Nandi, R. (2024). A comprehensive review of food waste valorization for the sustainable management of global food waste. *Sustain. Food Technol.* 2, 48–69. doi: 10.1039/d3fb00156c

Sathish, T., Saravanan, R., Depoures, M. V., Palanikumar, B., Rajasimman, M., and Rajkumar, S. (2023). Environmental remediation at vegetable marketplaces through production of biowaste catalysts for biofuel generation. *Sci. Rep.* 13:5067. doi: 10.1038/s41598-023-31687-5

Serrão, J. E., Plata-Rueda, A., Martínez, L. C., and Zanuncio, J. C. (2022). Side-effects of pesticides on non-target insects in agriculture: a mini-review. *Sci. Nat.* 109:17. doi: 10.1007/s00114-022-01788-8

Shahraki, S., Shiri, F., Heidari Majd, M., and Dahmardeh, S. (2019). Investigating the biological potency of novel lanthanum (III) amino acid complex: MCF-7 breast cancer cell line, BSA and β-LG as targets. *J. Iran. Chem. Soc.* 16, 301–313. doi: 10.1007/s13738-018-1508-7

Sharma, P., Bano, A., Verma, K., Yadav, M., Varjani, S., Singh, S. P., et al. (2023). Food waste digestate as biofertilizer and their direct applications in agriculture. *Bioresour. Technol. Rep.* 23:101515. doi: 10.1016/j.biteb.2023.101515

Siddiqui, Z., Hagare, D., Liu, M. H., Panatta, O., Hussain, T., Memon, S., et al. (2023). A food waste-derived organic liquid fertiliser for sustainable hydroponic cultivation of lettuce, cucumber and cherry tomato. *Food Secur.* 12:719. doi: 10.3390/foods12040719

Singh, M. P., and Singh, V. K. (2012). Biodegradation of vegetable and agrowastes by Pleurotus sapidus: a novel strategy to produce mushroom with enhanced yield and nutrition. *Cell. Mol. Biol.* 58, 1–7

Singh, S., Kumar, V., Datta, S., Dhanjal, D. S., Sharma, K., Samuel, J., et al. (2020). Current advancement and future prospect of biosorbents for bioremediation. *Sci. Total Environ.* 709:135895. doi: 10.1016/j.scitotenv.2019.135895

Sohany, M., Tawakkal, I. S. M. A., Ariffin, S. H., Shah, N. N. A. K., and Yusof, Y. A. (2021). Characterization of anthocyanin associated purple sweet potato starch and peel-based pH indicator films. *Food Secur.* 10:2005. doi: 10.3390/foods10092005

Sonnenberg, A. S., Baars, J. J., Obodai, M. A. R. Y., and Asagbra, A. G. N. E. S. (2015). Cultivation of oyster mushrooms on cassava waste. *Food Chain* 5, 105–115. doi: 10.3362/2046-1887.2015.007

Stenmarck, Å., Jensen, C., Quested, T., and Moates, G. (2016). Estimates of European food waste levels. *IVL Report C* 186:4721. doi: 10.13140/RG.2.1.4658.4721

Stylianou, M., Laifi, T., Bennici, S., Dutournie, P., Limousy, L., Agapiou, A., et al. (2023). Tomato waste biochar in the framework of circular economy. *Sci. Total Environ.* 871:161959. doi: 10.1016/j.scitotenv.2023.161959

Subbaiya, R., Aakash, B., Shanmugaraja, A., Devika, R., Chozhavendhan, S., Vinoth, S., et al. (2019). Vegetable waste as an alternate plant tissue culture Media for Laboratory and Industry. *Res. J. Pharm. Technol.* 12, 1521–1528. doi: 10.5958/0974-360X.2019.00252.X

Syarifuddin, N. A., Rizal, M., Riyadhi, M., and Wahdi, A. (2022). Libido and sperm quality of the Etawah cross-breed fed urea Moringa molasses multinutrient block supplement. *J. Hunan Univ. Nat. Sci.* 49, 131–140. doi: 10.55463/issn.1674-2974.49.3.14

Szewczyk, A., Andres-Mach, M., Zagaja, M., Kaczmarczyk-Ziemba, A., Maj, M., and Szala-Rycaj, J. (2023). The effect of a diet enriched with Jerusalem artichoke, inulin, and fluoxetine on cognitive functions, neurogenesis, and the composition of the intestinal microbiota in mice. *Curr. Issues Mol. Biol.* 45, 2561–2579. doi: 10.3390/cimb45030168

Taghavi, E., Abdul Salam, A. S., Anarjan, N., Nillian, E., and Lani, M. N. (2022). Onion essential oil-in-water emulsion as a food flavoring agent: effect of environmental stress on physical properties and antibacterial activity. *Int. J. Food Sci.* 2022, 1363590–1363511. doi: 10.1155/2022/1363590

Tanasa, A., and Suteu, D. (2022). Biovegetal wastes used as biosorbent for removal of chemical pollutants from wastewater. *Res. J. Agric. Sci* 53, 227–232.

Teshome, E., Teka, T. A., Urugo, M. M., Nandasiri, R., Gemede, H. F., Rani, I., et al. (2024). Extraction methods, industrial uses, and nutritional benefits of vegetable byproducts. *Int. J. Veg. Sci.* 30, 334–363. doi: 10.1080/19315260.2024.2369892

Toro-Márquez, L. A., Merino, D., and Gutiérrez, T. J. (2018). Bionanocomposite films prepared from corn starch with and without nanopackaged Jamaica (*Hibiscus sabdariffa*) flower extract. *Food Bioprocess Technol.* 11, 1955–1973. doi: 10.1007/s11947-018-2160-z

Trovaslet, M., Kapel, R., Ravallec-Plé, R., Mouni, F., Clarisse, M., Faille, C., et al. (2007). Secretagogue and bacteriostatic active fractions derived from a peptic hydrolysate of alfalfa RuBisCO small purified subunit. *J. Sci. Food Agric.* 87, 534–540. doi: 10.1002/jsfa.2754

Udenigwe, C. C., and Aluko, R. E. (2012). Food protein-derived bioactive peptides: production, processing, and potential health benefits. *J. Food Sci.* 77, R11–R24. doi: 10.1111/j.1750-3841.2011.02455.x

Ueda, J. M., Pedrosa, M. C., Heleno, S. A., Carocho, M., Ferreira, I. C., and Barros, L. (2022). Food additives from fruit and vegetable by-products and bio-residues: a comprehensive review focused on sustainability. *Sustain. For.* 14:5212. doi: 10.3390/su14095212

UNEP (2021). *Food Waste Index Report 2021*. Nairobi, Kenya: UNEP.

Valdés, A., Burgos, N., Jiménez, A., and Garrigós, M. C. (2015). Natural pectin polysaccharides as edible coatings. *Coatings* 5, 865–886. doi: 10.3390/coatings5040865

Valisakkagari, H., Chaturvedi, C., and Rupasinghe, H. V. (2024). Green extraction of phytochemicals from fresh vegetable waste and their potential application as cosmeceuticals for skin health. *PRO* 12:742. doi: 10.3390/pr12040742

Van Ginkel, S. W., and Logan, B. (2005). Increased biological hydrogen production with reduced organic loading. *Water Res.* 39, 3819–3826. doi: 10.1016/j.watres.2005.07.021

Vazquez-Armenta, F. J., Ayala-Zavala, J. F., Olivas, G. I., Molina-Corral, F. J., and Silva-Espinoza, B. A. (2014). Antibrowning and antimicrobial effects of onion essential oil to preserve the quality of cut potatoes. *Acta Aliment.* 43, 640–649. doi: 10.1556/AAlim.43.2014.4.14

Vázquez-Durán, A., Nava-Ramírez, M. D. J., Hernández-Patlán, D., Solís-Cruz, B., Hernández-Gómez, V., Téllez-Isaías, G., et al. (2021). Potential of kale and lettuce residues as natural adsorbents of the carcinogen aflatoxin B1 in a dynamic gastrointestinal tract-simulated model. *Toxins* 13:771. doi: 10.3390/toxins13110771

Verma, T., Aggarwal, A., Dey, P., Chauhan, A. K., Rashid, S., Chen, K. T., et al. (2023). Medicinal and therapeutic properties of garlic, garlic essential oil, and garlic-based snack food: an updated review. *Front. Nutr.* 10:1120377. doi: 10.3389/fnut.2023.1120377

Visco, A., Scolaro, C., Facchin, M., Brahimi, S., Belhamdi, H., Gatto, V., et al. (2022). Agri-food wastes for bioplastics: European prospective on possible applications in their second life for a circular economy. *Polymers* 10:2752. doi: 10.3390/polym14132752

Voge, J., Newiger-Dous, T., Ehrlich, E., Ermann, U., Ernst, D., Haase, D., et al. (2023). Food loss and waste in community-supported agriculture in the region of Leipzig, Germany. *Int. J. Agric. Sustain.* 21:2242181. doi: 10.1080/14735903.2023.2242181

Von Grebmer, K., Bernstein, J. L., Hammond, F., Wiemers, M., Chéilleachair, R. N., Foley, C., et al. (2019). *Global hunger index: the challenge of hunger and climate change; Welthungerhilfe: Bonn, Germany; concern worldwide: Dublin, Ireland, 2019*. Available online at: https://coilink.org/20.500.12592/r19173 (Assessed Sep 3, 2024).

Wahyuningsih, S., Wulandari, L., Wartono, M. W., Munawaroh, H., and Ramelan, A. H. (2017). The effect of pH and color stability of anthocyanin on food colorant. *In IOP Conf. Ser. Mater. Sci. Eng.* 193:012047. doi: 10.1088/1757-899X/193/1/012047

Wang, L., Deng, J., Yang, X., Hou, R., and Hou, D. (2023). Role of biochar toward carbon neutrality. *Carbon Res.* 2:2. doi: 10.1007/s44246-023-00035-7

Wang, R., Wang, X., and Sun, Y. (2017). One-step synthesis of self-doped carbon dots with highly photoluminescence as multifunctional biosensors for detection of iron ions and pH. *Sens. Actuators B Chem.* 241, 73–79. doi: 10.1016/j.snb.2016.10.043

Wei, H., Junhong, T., and Yongfeng, L. (2016). Utilization of food waste for fermentative hydrogen production. *Phys. Sci. Rev.* 1:20160050. doi: 10.1515/psr-2016-0050

Yang, S., Kawamura, Y., and Yoshikawa, M. (2003). Effect of rubiscolin, a delta opioid peptide derived from rubisco, on memory consolidation. *Peptides* 24, 325–328. doi: 10.1016/s0196-9781(03)00044-5

Yang, X., Igalavithana, A. D., Oh, S. E., Nam, H., Zhang, M., Wang, C. H., et al. (2018). Characterization of bioenergy biochar and its utilization for metal/metalloid immobilization in contaminated soil. *Sci. Total Environ.* 640-641, 704–713. doi: 10.1016/j.scitotenv.2018.05.298

Yao, S., Li, X., Cheng, H., Zhang, C., Bian, Y., Jiang, X., et al. (2019). Resource utilization of a typical vegetable waste as biochars in removing phthalate acid esters from water: a sorption case study. *Bioresour. Technol.* 293:122081. doi: 10.1016/j.biortech.2019.122081

Ye, C. L., Dai, D. H., and Hu, W. L. (2013). Antimicrobial and antioxidant activities of the essential oil from onion (*Allium cepa* L.). *Food Control* 30, 48–53. doi: 10.1016/j.foodcont.2012.07.033

Yin, J., Ju, Y., Qian, H., Wang, J., Miao, X., Zhu, Y., et al. (2013). Nanoplastics and microplastics may be damaging our livers. *Toxics* 10:586. doi: 10.3390/toxics10100586

Zagury, Y., David, S., Edelman, R., Brill, R. H., and Livney, Y. D. (2021). Sugar beet pectin as a natural carrier for curcumin, a water-insoluble bioactive for food and beverage enrichment: formation and characterization. *Innov. Food Sci. Emerg. Technol.* 74:102858. doi: 10.1016/j.ifset.2021.102858

Zhang, B., Huang, C., Zhao, H., Wang, J., Yin, C., Zhang, L., et al. (2019). Effects of cellulose nanocrystals and cellulose nanofibers on the structure and properties of polyhydroxybutyrate nanocomposites. *Polymers* 11:2063. doi: 10.3390/polym11122063

Zhang, H., Lei, T., Lu, S., Zhu, S., Li, Y., Zhang, Q., et al. (2022). Study on comparisons of bio-hydrogen yield potential and energy conversion efficiency between stem and leaf of sweet potato by photo-fermentation. *Fermentation* 8:165. doi: 10.3390/fermentation8040165

Zhang, X., Sun, Z., Cai, J., Wang, J., Wang, G., Zhu, Z., et al. (2020). Effects of dietary fish meal replacement by fermented moringa (*Moringa oleifera* lam.) leaves on growth performance, nonspecific immunity and disease resistance against *Aeromonas hydrophila* in juvenile gibel carp (*Carassius auratus gibelio* var. CAS III). *Fish Shellfish Immunol.* 102, 430–439. doi: 10.1016/j.fsi.2020.04.051

Zhang, Y. H. P., and Lynd, L. R. (2006). A functionally based model for hydrolysis of cellulose by fungal cellulase. *Biotechnol. Bioeng.* 94, 888–898. doi: 10.1002/bit.20906