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Valorization of carrot, cabbage, and red beet by-products – A review

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Approximately 30% of vegetables end up as by-products during processing. Vegetable by-products have traditionally been used as animal feed, soil improvers, or raw material for biogas. In this literature review, we examine and discuss studies concerning the utilization of cabbage, carrot, and red beet by-products in a wide variety of applications, including technical applications. These vegetables are widely cultivated in northern climates as well as around the world, and there is a need to outline potential uses for their by-products. Numerous product ideas and research results exist concerning the use of by-products in food, feed, pharmaceuticals and cosmetics, biosorbents, composites and films, energy products, soil amendments and pesticides, enzymes, dyes and biosurfactants, and electrical products. Food and food additives were the most examined targets of carrot, cabbage, and red beet by-product valorization. These studies could be used, for example, in creating a company's by-product utilization strategy. High-value biochemicals, tailored nutraceuticals, feed additives, bioplastics, or biofuels may be realistic options in large-scale production. Environmental, safety, and economic aspects must be taken into account when utilizing by-products.

Key words: side-stream, *Daucus carota* L., *Brassica oleracea* L. var. *capitata*, *Beta vulgaris* L. var. *conditiva*, utilization

Introduction

Roughly one-third of all food, approximately 1.3 billion tonnes, produced for human consumption is lost globally per year (FAO 2011). Both globally (FAO 2011, Sagar et al. 2018, FAO 2019) and in Europe (Caldeira et al. 2019), fruits and vegetables are the largest groups of food waste. Although the largest share of food is wasted at the consumption stage, the processing stage is considered a close second, and it can result in about 30% of vegetables going to waste (Sagar et al. 2018, EU 2020). At the primary production and processing stages of the vegetable value chain, vegetable loss is due to managerial, financial, and technical issues, including insufficient harvesting facilities, inadequate harvesting techniques, and a lack of information on climatic conditions and marketing systems (FAO 2011). For example, in Sweden, one third of the carrots (*Daucus carota* L.) produced are used for purposes other than food (Olsson 2023). Data on the exact waste quantities produced through food processing are very limited, and no official data are issued annually by the EU.

Waste is defined as any substance or object that the holder discards, or intends to discard, or is required to discard. A by-product, on the other hand, is a substance or object resulting from a production process whose primary aim is not the production of that item. The term "side stream" broadly refers to by-products or waste generated during industrial processes (EU Directive 2008/98/EC). Residue refers to a small amount of matter that remains after the main part has been used, removed, or has otherwise gone. By-products of vegetable processing include solid residues of peels, skins, seeds, stems, and pulp. Pomace is the by-product of carrot juicing, and mash or pulp is the by-product of the carrot peeling and cutting process (Duval 2020). For example, up to 40% of the outer leaves and core of cabbages *(Brassica oleracea* L. var. *capitata)* are considered by-products, and up to 30% of the total production is estimated not to be utilized as food (Zhang et al. 2022). Large amounts of waste are also generated during the trimming process (Mago et al. 2022). Vegetable waste thus involves a loss of valuable biomass and nutrients (Plazzotta et al. 2020, Marcillo-Parra et al. 2021).

Many original study articles exist concerning the by-products of carrots, cabbage, and red beets (*Beta vulgaris* L. var. *conditiva*), but their utilization as a whole has not been widely examined, although reviews concerning other vegetables are available. These three vegetables, particularly important in northern climates, are the focus of this review.

By-products of carrot, cabbage, and red beet are currently often used as such as animal feed (Nilnakara et al. 2009, Tumbas Šaponjac et al. 2016, Battistella Lasta et al. 2019, Kaur et al. 2022b), in landfills (Kaur et al. 2022b), as fertilizer (Nilnakara et al. 2009) or composted (Battistella Lasta et al. 2019). Their nutritional and biological

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potential could offer benefits for health promotion (Galanakis 2012, Ben-Othman et al. 2020), endorsing business (Coman et al. 2020, Galanakis 2020), and decreasing negative environmental impacts (Lai et al. 2017, Majerska et al. 2019). The compounds in carrot, cabbage, and red beet by-products (Table 1) are the basis for several valorization options presented in this review. Utilization of the compounds in different valorization targets is discussed in the sections in question. Most valorization options require the use of processing technologies. These include, e.g., drying, blanching, fermentation, extraction, extrusion, encapsulation, thermochemical technologies, anaerobic digestion, and composting. In some cases, also the fractionation technique for separating the desired component from the bulk by-product, e.g., protein from cabbage leaves (Nynäs et al. 2021), needs development. Although important, technical feasibility, including pre-treatment, extraction and production methods, is outside the scope of this review.

Table 1. Compounds of carrot, cabbage and red beet as a basis for valorization of by-products of these vegetables

Vegetable	Beneficial compounds	Reference
Carrot (*Daucus carota* L.)	Carotenoids (carotene, lutein), dietary fibers, phytochemicals (polyphenols)	Sharma et al. 2012, Anal 2018, Amin et al. 2021, Sepúlveda et al. 2021
Cabbage *(Brassica oleracea* L. var. *capitata*)	Dietary fibers, protein, bioactive compounds, vitamins, minerals, sulphur-containing amino acids, antioxidants (ascorbic acid, phenolic compounds), carotenoids, glucosinolates, phytochemicals, tocopherols	Wennberg et al. 2003, Kim et al. 2004, Liang 2016, Singh et al. 2006, Jongaroontaprangsee et al. 2007, Kusznierewicz et al. 2008, Nilnakara et al. 2009, Singh et al. 2010, Samec et al. 2011, Gül et al. 2013, Šedlar et al. 2021
Red beet (*Beta vulgaris* L. var. *conditiva*)	Protein, fiber, lipids, phenolics, nitrates, flavonoids, carotenoids, betalains (betacyanin, betaxanthins), vitamins, minerals, dietary fiber, polyphenols	Vulić et al. 2013, 2014, Porto Dalla Costa et al. 2017, Chauhan and Rajput 2018, Kohajdová et al. 2018, Kaur et al. 2021, Nutter et al. 2021, Petrovic et al. 2021, Sedlar et al. 2021, Zin and Bánvölgyi 2021, 2022

The aim of this literature review is to examine potential applications for by-products of carrot, cabbage, and red beet. Valorization of the by-products is discussed in terms of potential product sectors, as well as environmental and economic aspects.

Material and methods

For a narrative literature review (Green et al. 2006), publications about the valorization of the by-products of the vegetables in question were searched using the database of Helka libraries (UH 2025). For the valorization options, combinations of two search terms such as carrot and by-product were used. Carrot and cabbage were clear search terms, while for red beet, also the terms beetroot and red beetroot were used. As presented in the introduction, the by-product terminology used in literature is vague. Thus, for by-product, also alternative search terms byproduct, waste, reject, and residue were used.

Experimental studies were selected for further examination. The focus of this study is on by-products, which was a selection criterion. However, the experimental studies focusing on by-products included studies made with by-products from agriculture (e.g., leaves of carrots) or the processing industry (e.g., mash from juice processing), vegetable rejects, and normal vegetables as models for by-products. Since there was plenty of literature, the selection was made first by focusing on peer-reviewed articles and secondly by obtaining a versatile collection of valorization options, products, and utilization ideas. The second author conducted the main literature search and analysis of the articles, but all authors participated in the discussion and further processing of the data.

Valorization options for the by-products of carrot, cabbage and red beet

Valorization options for the focus vegetables were divided into nine product sectors. Food and nutraceutical applications, as the most examined sector, are presented first, followed by feed, pharmaceuticals, and cosmetics. Technical uses include biosorbents, composites and films, energy products, soil amendments and pesticides, enzymes, dyes and biosurfactants, and electrical applications.

Food ingredients and additives

Plenty of research with an interest in utilizing the nutritional components of the vegetables (Table 1) has been conducted in the food sector, including nutraceuticals. More studies on carrots and red beets than on cabbage were available for the food sector (Table 2). Most studies showed that the by-products of these vegetables had potential uses, including a variety of possible applications in food, for example, as a colorant, antioxidant, and dietary fiber. However, unwanted side effects on sensory properties, e.g., taste, are sometimes a challenge (Kohajdová et al. 2018, Petrovic et al. 2021, Abdo et al. 2022). In addition, studies on an industrial production scale are called for.

In the case of carrots, the most examined by-product was the pomace, or pulp, resulting from juice pressing (Table 2), both from fresh and fermented raw materials (Janiszewska-Turak et al. 2021). Carrot leaves and tops showed potential for producing food additives (Leite et al. 2011, de Oliveira et al. 2015), while the peels were suitable for extracting carotenoids (de Andrade Lima et al. 2018), and for preparing dietary fiber (Chantaro et al. 2008) and jam (Hussein et al. 2015).

Some studies showed potential for cabbage waste as a raw material for functional foods and beverages (Table 2). Rashad and Abdou (2001) found cabbage whey to be a suitable substrate for cultivating edible fungi. Proteins derived from, e.g., red beet and cabbage leaves had good functional properties, as noted in Sedlar et al. (2021). Red beet leaves have been used, e.g., as an emulsifier (Ralla et al. 2019) and as an ingredient for bakery products (Asadi and Khan 2021). Red beet peel could be used as a preservative agent due to its antioxidant properties (El-Beltagi et al. 2022), but these properties of a beetroot peel extract have also been questioned (Šeremet et al. 2020). Red beet pomace has been found to have antibacterial (Vulić et al. 2013, Salamatullah et al. 2021), antiradical and hepatoprotective (Vulić et al. 2014), and anticandidal properties (Salamatullah et al. 2021).

Table 2. Studies of carrot, cabbage, and red beet by-products in food products and nutraceuticals as food additives or functional food ingredients

By-products as raw materials	Main components or compounds utilized	Reference
Carrot leaves	E.g., antioxidants, chlorophyll, fatty acids	Leite et al. 2011
	Ingredient of flour: omega-3 fatty acids	de Oliveira et al. 2015
Carrot peel	Dietary fiber, pectin, β-carotene, phenolics, antioxidants	Chantaro et al. 2008
	Dietary fiber, β-carotene, anthocyanins	Amany et al. 2010
	Proteins, dietary fibers, carbohydrates, sensory properties	Baljeet et al. 2014
	Physical properties of extrudates	Alam et al. 2015
	β-carotene, phenolics, antioxidants, antioxidant dietary fiber powder	Hussein et al. 2015
	Carotenoids	de Andrade Lima et al. 2018
	Inulinase enzyme, high-fructose syrup and fructo-oligosaccharides	Singh et al. 2018
	Single-cell protein source for noodles or bread	Razzaq et al. 2022, Khan et al. 2022
	Carotenoids, sensory properties	Šeregelj et al. 2022
Carrot pulp and mash	Carotenoids, polyphenols, oligosaccharides,	Duval 2020
	E.g., carotenoids, polyphenols	Amin et al. 2021
	Phenolic compounds, carotenoids, tocopherols	Araújo-Rodrigues et al. 2021
Carrot discards	Gelling agent pectin	Christiaens et al. 2015
	Pigments, fermentation products: carotenoids, sugars, acids	Ramos-Andrés et al. 2021
	Colour, carotenes	Kaur et al. 2022a, b
Cabbage outer leaves	Substrate for the cultivation of edible fungi for human food and supplements	Rashad and Abdou 2001
	Dietary fiber powder	Jongaroontaprangsee et al. 2007
	Antioxidants, vitamin C, colour	Nilnakara et al. 2009
	Beverages, nutraceuticals: polyphenols, glucosinolates	Gonzales et al. 2015

Red cabbage leaves	Dietary fiber, minerals	Brito et al. 2020
	Antioxidants, acid binding, dialysis retardation	Liang et al. 2019
	Anthocyanins	Patras 2019
	Polyphenols, antioxidants, food colourant	Zanoni et al. 2020
Red beet leaves	E.g., proteins, dietary fiber, fats, carbohydrates, phenolics, antioxidants, colour	Asadi and Khan 2021
	Polyphenols, betaxanthin, betacyanin	Nutter et al. 2021
Red beet peel	Flavourant, colourant, antioxidant: betalains, phenolics	Kujala et al. 2001
	Cookies: e.g., protein, fiber, sensory parameters	Chauhan and Rajput 2018
	Emulsifier for food and beverage products	Ralla et al. 2019
	Phenolic compounds, e.g., betanin, and betacyanins	Kujala et al. 2000
	Fiber, protein, phenolics, antioxidants, betacyanin, biological effects	Šeremet et al. 2020
	Betalains, phenolics, antioxidants	Zin and Bánvölgyi 2021
	Antioxidant, preservatives phenolic compounds: flavonoids, betalains, antiradical scavenging	El-Beltagi et al. 2022
	Betalain, phenolics, flavonoids	Zin and Bánvölgyi 2022
Red beet pomace	Phytochemical profile, antiradical, antimicrobial, and cytotoxic activities	Vulić et al. 2013
	Antioxidant effects	Vulić et al. 2014
	Ingredient in biscuits: betacyanins, polyphenols, antioxidant capacity	Hidalgo et al. 2018
	Source of dietary fiber in bakery products: proteins, dietary fiber	Kohajdová et al. 2018
	Candy enrichment: phenolics, betacyanin, betaxanthin, antioxidant capacity	Kumar et al. 2018
	Ingredient in yogurt: protein, fiber	Jovanović et al. 2021
	Fortification for functional dairy dessert: betalains	Kaur et al. 2021
	Liqueur: phenolics, antioxidants, colour	Petrović et al. 2021
Red beet peels, parings, stalks	Colour, antioxidants, dietary fiber, phenolics, betalain	Porto Dalla Costa et al. 2017
Red beet leaves and stems	Betacyanin, polyphenols	Aguirre Calvo et al. 2019
	Fortification of functional orange juice: flavonoids, betalain, radicals scavenging activity	Abdo et al. 2022
Red beet pulp and peel	Polyphenols, flavonoids, antioxidant and antimicrobial activity	Salamatullah et al. 2021

Feed ingredients and additives

Similar to food uses, many components of vegetable by-products (Table 1) are beneficial in animal feed. For example, dried cabbage waste is an excellent source of protein (Mahgoub et al. 2018). Animal feed is a basic utilization target for carrot (Aimaretti and Yibalo 2012, Bakshi et al. 2016) and cabbage (Nilnakara et al. 2009) discards, but the need for other valorization alternatives has been raised (Aimaretti and Yibalo 2012). As an example of a new type of utilization, Rashad and Abdou (2001) found cabbage whey to be a suitable substrate for cultivating edible fungi, also for feed use. Castrica et al. (2018) estimated pet food to be the most concrete strategy for using food waste as animal feed within the European context, but most of the studies focus on animals other than pets (Table 3).

Table 3. Studies of carrot, cabbage, and red beet by-products in feed and pet food ingredients and additives

By-products as raw materials	Product or application examples	Reference
Carrot pomace	Insect feed, e.g., proteins and carotenoids	Rovai et al. 2022
Carrot extract	Fermented for feed and food additives	Stockhammer et al. 2009
Carrot discards	Supplement for prawn feed vinasse	Garces and Heinen 1993
	Forage for egg-laying hens	Hammershøj et al. 2010
	Co-fermented carrot and brewer's yeast, animal feed	Aimaretti et al. 2012
Cabbage outer leaves	Fermented cabbage for calf feed	Mukodininghsih et al. 2019a, b
	Ruminant (sheep) feed, goat feed	Ngu and Ledin 2005, Wadhwa et al. 2006, de Evan et al. 2019
	Fermented extract as a starter for rice bran fermentation	Setya Utama et al. 2013
	Poultry feed	Mustafa and Baurhoo 2018
	Rabbit feed	Nguen et al. 2009
	Snail feed, e.g., proteins and fibers	Omolara and Olaleye 2010, Babalola 2018
	Livestock feed	Mahgoub et al. 2018
	House cricket feed, e.g., proteins and carbohydrates	Morales-Ramos et al. 2020
	Substrate for cultivation of fungi for feed	Rashad and Abdou 2001
Red beet discards	Fermented red beets for lamb feed	Nkosi and Ratsaka 2010
Red beet pomace	Dog food	Jovanović et al. 2021

Ruminants have the capacity to utilize fibrous materials because of their rumen microbiota, which enables the use of many by-products in their feeds (Mirzaei-Aghsaghali and Maheri-Sis 2008), either fresh (whole or chopped), as dried and ground meal, or as silage (de Rezende et al. 2015, Bakshi et al. 2016, Du et al. 2021, Ren et al. 2021). Rust and Buskirk (2008) estimated 40% (DB, dry basis) carrot being suitable for beef cattle, and carrot was also mentioned as being suitable for cows (15.9 kg/cow/day), while a carrot addition of 5 kg/cow/day was reported to have beneficial effects on milk quality (Nalecz–Tarwacka et al. 2003). As a disadvantage for ruminant feeds, carrot and red beet pomaces increased the gas formation related to digestible organic matter (Giller et al. 2021). Cabbage waste leaves are potential in goat feeds (Ngu and Ledin 2005, Wadhwa et al. 2006), but sulfur toxicity in cabbage wastes and its effect on the feed flavor should be taken into account (De Evan et al. 2019). Ensiling and fermentation of vegetable by-products may enhance the acceptance, performance, and growth of animals, such as in carrot feed for steers (Laflamme 1992) and outer leaves of cabbage for calves (Mukodiningsih et al. 2019a).

Concerning poultry feed, carrot by-products had positive effects on the quality of eggs (Sidker et al. 1998, Hammershøj et al. 2010) and hen welfare (Steenfeldt et al. 2007). Cabbage leaf residues could improve nutrient utilization and egg quality (Mustafa and Baurhoo 2018). Cabbage has also been used in rabbit feed (Tsutsmi et al. 1967), with beneficial effects on vitamin A (Pirie and Wood 1946), but the effect of cabbage on growth rate varied from positive (Nguen et al. 2009) to not beneficial (Hang et al. 2011).

Carrot feed as a source of carotenoids improved the colour and sensory properties of catla, a carp fish (Weerakkody and Cumaranatunga 2016), the color of cichlid (Kop et al. 2010), and the colour (Lili et al. 2018) and growth (Wagde et al. 2018) of the swordtail, an ornamental aquarium fish, while gilthead seabream colour was not improved by carrot feed (Wassef et al. 2010). Carrot and carrot tops increased prawn pigmentation, although this was not considered an important feature (Garces and Heinen 1993).

Insects can utilize vegetable by-products as feed and convert the organic waste material of, e.g., carrots (Oonincx et al. 2015, Varelas 2019, Aristi et al. 2020, Rovai et al. 2022) or cabbage (Aristi et al. 2020, Morales-Ramos et al. 2020, Pinotti and Ottoboni 2021) into biomass that can be used as a raw material for human food and/or animal feed or technical applications (van Peer et al. 2021). A diet enriched with, e.g., shredded carrots or cabbages improved the growth of mealworm larvae that were considered as human food ingredients (Liu et al. 2020). The initial interest being in human food (Oonincx and Boer 2012, Van Broekhoven et al. 2015, Rovai et al. 2022) or food and feed (Oonincx et al. 2015), carrot was used as a basic feed substance for mealworms, e.g., to provide moisture. Carrot waste was promising for the fat content of black soldier fly larvae (Aristi et al. 2020). Black soldier flies (Oonincx et al. 2015, Aristi et al. 2020) and cockroaches (Oonincx et al. 2015) fed by vegetables were intended to be feed for other animals. Syahrizal et al. (2022) observed that a mixture of palm kernel meal and cabbage waste was among the most favorable feed for black soldier flies that could be used for fish feed. Omolara and Olaleye (2010) and Babalola (2018) observed that snails can utilize cabbage waste as their sole feed. Carrots are also used as feed for insects grown for pest management, such as flies (Mainali et al. 2019).

Pharmaceuticals and cosmetics

Case studies of carrot, cabbage, or red beet by-products as pharmaceuticals were often marginal, and the potential for food, nutraceutical, and pharmaceutical uses was often combined (Table 4). Examples of promising results include red beet stalks and leaves by-products in obesity control (Micheletti Lorizola et al. 2021) and red beet pomace having cytotoxic effects against carcinoma cells (Vulic et al. 2013). Vegetable pigments could be used in pharmaceutical products (de Andrade Lima et al. 2018, Ramos-Andrés et al. 2021) and pigments and odorous substances in creams and perfumes (Naviglio et al. 2019). Components of vegetable by-products shown to have potential as health products include β-carotene (Roohinejad et al. 2014, Purohit and Gogate 2015), insoluble fiber (Ma et al. 2016), and phenolic compounds (El-Sawi et al. 2022) in carrot waste, organic acids (Selder et al. 2021), phytochemicals (Šamec et al. 2011), and phenolics (Gonzales et al. 2015) in cabbage waste, and betalains and polyphenolic compounds in red beet waste (Lazăr et al. 2021).

Table 4. Studies of carrot, cabbage, and red beet by-products in pharmaceutical products and cosmetics

By-products as raw materials	Product or application examples: main components or compounds utilized	Reference
Carrot peel	Pharmaceuticals or cosmetics: carotenoids	de Andrade Lima et al. 2018
	Pharmaceutical applications: carotenoids	El-Sawi et al. 2022
Carrot pomace	Pharmaceuticals, functional ingredient for intestinal health	Roohinejad et al. 2014
	Pharmaceutical against cancer and microbial infections: phenolics, flavonoids	Purohit and Gogate 2015
	Dietary fiber	Ma et al. 2016
Carrot discards	Pigments for pharmaceutical industry: sugars, acids	Ramos-Andrés et al. 2021
Cabbage outer leaves	Additives for cosmetics (red cabbage): polyphenols, glucosinolates	Gonzales et al. 2015
	Pharmaceutics, food, and feed: butyric, valeric, and caproic acids	Selder et al. 2021
	Antibacterial and antifungal lipophilic mixture for the clinical, veterinary, and agricultural fields	Arrais et al. 2022
Red beet peel	Pharmaceuticals and nutraceuticals: betalains, polyphenols	Lazăr et al. 2021
Red beet pomace	Pharmaceutical and cosmetic industry: phytochemical profile, antiradical, antimicrobial and cytotoxic activities	Vulic et al. 2013
	Encapsulated extract for pharmaceuticals, food additives: phenolics, flavonoids, betalain	Tumbas Šaponjac et al. 2016
	Medicinal and food applications: betacyanin, betaxanthin, phenolics, antioxidants	Kuswaha et al. 2018
Red beet leaves and stems	Nutraceuticals, functional food, or pharmaceuticals: phenolics	Battistella Lasta et al. 2019
	Supplementation, adjuvant in obesity	Micheletti Lorizola et al. 2021

Biosorbents

Activated carbon was the most common active component from carrot or cabbage by-products in biosorbent studies (Table 5), and it was examined mostly for wastewater purification and, in a few studies, for purifying soil and vapor. Lignocellulose-based biosorbents were also common for wastewater purification. Single studies concerning carrot by-products in biosorbents for wastewater were based on pectin (Hastuti et al. 2018) and peroxidase enzyme (Joel et al. 2020), while one study focused on the bioremediation of polluted soil

(Hamoudi-Belarbi et al. 2018). Regardless of the active component or structure examined, the by-products examined in most of the studies showed potential as biosorbent materials, with cabbage being the only exception in Hossain et al. (2014) and Xue et al. (2019).

Table 5. Studies of carrot, cabbage, and red beet by-products in biosorbents

By-products as raw materials	Product or application examples (potential raw material, active component)	Reference
Carrot discards	Biochar/active carbon for removing phosphorus from wastewater	de Carvalho Eufrásio Pinto et al. 2019
	Biochar/active carbon for dye removal from wastewater	Hira et al. 2020, Moradi et al. 2021
Carrot residue or discards	Lignocellulose as biosorbent/absorbent for heavy metal removal	Nasernejad et al. 2005, Bhatti et al. 2010
Carrot peel and pulp	Composite PET (Polyethylene terephthalate) adsorbent containing tomato and carrot for removing cobalt from wastewater	Changmai et al. 2018
Carrot peel	Biostimulation medium for bioremediation of crude petroleum	Hamoudi-Belarbi et al. 2018
	Pectin as biosorbent for heavy metals from wastewater	Hastuti et al. 2018
Carrot pulp	Biochar for heavy metal fractionation in contaminated soil	Gholami and Rahimi 2021
Carrot leaves and stems	Lignocellulose as biosorbent for removing dyes from wastewater	Kuswaha et al. 2014
Cabbage outer leaves	Lignocellulose as biosorbent/adsorbent for removing heavy metals or dyes from wastewater	Hossain et al. 2014, Wekoye et al. 2020
	Peroxidase enzyme for biodegradation of phenol and synthetic dyes from wastewater	Joel et al. 2020
	Activated carbon as adsorbent for mercury vapour removal	Vakili et al. 2021a, b
	Biochar for purifying off-gas or removing VOCs	Zhang et al. 2022
Red beet fiber	Lignocellulose as biofilter/adsorbent for removing dyes and heavy metals from wastewater, hard water softener	Rima et al. 2014

Composites, films, and packages

Using carrot and red beet discards or waste in composites and packages has been examined in some studies (Table 6), all of which showed that carrot or red beet by-products have at least preliminary potential in the production of films and packaging materials. The most typical end products examined or mentioned were food packages (Tran et al. 2017, Otoni et al. 2018, Perotto et al. 2018, Sogut and Cakmak 2020, Amoroso et al. 2022, Rodríguez-Félix et al. 2022), while the end product was not clearly specified in the remaining studies (Table 6).

Table 6. Valorization studies of carrot and red beet by-products in composites, films, and packages

By-products as raw materials	Product or application examples	Reference
Carrot pomace	Cellulose nanofibers for, e.g., reinforcement in polymer composites	Berglund et al. 2016
	Cellulose and nanocellulose film	Szymanska-Chargot et al. 2019
Carrot peel	Cellulose nanofibers for biocomposites for packaging	Otoni et al. 2018
Carrot discards and pulp	Cellulose nanofibers for bioplastics	Perotto et al. 2018
Carrot discards	Cellulose nanofiber film for packaging	Amoroso et al. 2022
	Dietary fibers, syrup to produce lactic acid for biodegradable plastic	Salvañal et al. 2021
Carrot pulp	Fibers and microcrystalline cellulose, packaging films	Sogut and Cakmak 2020
Red beet discards, peel	Biocomposite for packaging for pharmaceutical, medical, and food applications	Tran et al. 2017
Red beet pomace	Active food packaging	Rodríguez-Félix et al. 2022

Energy products

Energy products made from vegetable by-products include biogas, ethanol, and biodiesel. Cabbage (Solowski et al. 2019, Wei et al. 2021, Czubaszek et al. 2022), red beet (Surendran and Shanmugam 2021), and mixtures of vegetable wastes containing carrot (Yang and Cosolini 2019) and carrot and cabbage (Ravi et al. 2018) showed potential for biogas production. In some studies, co-fermentation of a mixture of cabbage waste and other raw materials produced more biogas than the wastes separately (Bozym et al. 2015, Wu et al. 2016, Mu et al. 2017), but opposite results have also been obtained (Arifan et al. 2021). Ethanol was produced from carrot discards (Aimaretti and Yibalo 2012, Aimaretti et al. 2012) or pomace (Yu et al. 2013, Khoshkho et al. 2022) through fermentation, while the residue could be used as animal feed. Biodiesel was prepared from carrot pomace by transesterification (Karatay et al. 2019, 2020), carrot being the growth medium or carbon source for microbial lipid production.

Soil amendments and pesticides

Improving soil properties or fertilization are the most common applications of vegetable by-products for agricultural purposes, while only a few studies have focused on pesticide use. Processed vegetable residues are used in agriculture mainly in the form of biochar, as residues from anaerobic digestion in energy production, or as compost. Cabbage was the most examined vegetable for this application sector (Table 7).

In agriculture, biochar can be used in various ways. As a soil ameliorant, it is used to optimize soil structure and composition, and to increase the availability of nutrients and the water retention capacity of the soil. Biochar buried in the soil, either as such or as a compost additive, serves as a long-term carbon storage, increases soil health by limiting the availability of pesticides and heavy metals, and contributes to the improvement of plant growth and crop production by affecting soil microbiology and enzyme activity (Enaime and Lübken 2021). Biochar as a soil amendment was discussed by Bakshi et al. (2021). Biochar can also be used as animal feed (Enaime and Lübken 2021). Most of the studies on the removal of contaminants from water or more widely from the environment (Table 8) focus on heavy metals. However, phosphorus, in particular, is relevant for agriculture. Carrot or cabbage by-products have shown potential as raw materials of biochar (de Carvalho Eufrásio Pinto et al. 2019, Pradhan et al. 2020a, b).

Anaerobic digestion produces biogas and digestate as a co-product, which can be used as fertilizer. Composting as a treatment of cabbage for soil amendment applications showed promising results in most studies (Table 7). Studies focusing on other treatments or active components for soil improvement were few: polymer gel from cabbage waste (Zhang et al. 2021) and lime mud from red beet juice production (Ławińska et al. 2020) showed potential, while carrot acid extracts did not (Suzuki et al. 2001) (Table 7). Results from studies examining the utilization of cabbage waste for biopesticides varied from positive (Zhang et al. 2022) to unpromising (Roshan-Bakhsh et al. 2019, Supyani et al. 2021).

Table 7. Studies of by-product use in soil amendments and pesticides

By-products as raw materials	Product or application examples	Reference
Cabbage outer leaves	Co-composting with phosphate rock	Walker et al. 2012
	Co-composting with poultry manure	Saleem et al. 2017, 2018
	Composting: carrier of fungi, control of plant pathogens in soil	Wolna-Maruwka et al. 2019
	Composting with fungus	Ntsobi et al. 2021
	Vermicomposting: soil amendment	Mago et al. 2022
Red cabbage outer leaves	Biochar for use in P recovery and as fertilizer	de Carvalho Eufrásio Pinto et al. 2019
Cabbage outer leaves	Extracts by various solvents, natural nematicide	Roshan-Bakhsh et al. 2019
	Biochar for soil amendment, balancing soil properties	Pradhan et al. 2020a&b
	Fermentation extract with cow urine to produce biopesticide	Supyani et al. 2021
	Applications of superabsorbent polymer gel, e.g. soil amendment	Zhang et al. 2021
	Extract before pyrolysis for use as pesticides or insecticides, biochar, activated carbon, pyrolytic liquid, pyrolytic gas	Zhang et al. 2022
Carrot pomace	Acid extract of carrot pomace as a plant growth substance	Suzuki et al. 2001
Red beet pomace	Carbonation lime mud, raw material for producing mineral–organic fertilizers	Ławińska et al. 2020

Enzymes, dyes, and biosurfactants

Some studies showed good potential for using carrot or cabbage waste in enzyme production or for using red color extract from cabbage or red beet as a textile dye (Table 8). Some results were contradictory: the study by George and Jayachandran (2008) did not favor carrot peels in biosurfactant production, while positive results were obtained by Andrade et al. (2014) for red beet waste from juice production for the same purpose. Red beet skin was the most promising for producing biocatalysts to produce pure compounds for several fields of application (Vandenberghe et al. 2013).

Table 8. Studies of carrot, cabbage, and red beet by-products in enzyme, dye, and biosurfactant production

By-products as raw materials	Product or application examples	Reference
Vegetable by-products, e.g., carrot peel	Growing media for extremophile biomass production, enzymes and polymers	Di Donato et al. 2011
Carrot peel	Biosurfactants	George and Jayachandran 2008
Carrot pulp	Fatty acids precursor, fibrous booster to maintain in wastewater treatment	Hastuti et al. 2018
Cabbage outer leaves	Enzymes for dry-cleaning, detergents, meat processing, cheese making, silver recovery, digestive and medical treatments, waste management	Madhumithah et al. 2011
	Enzymes for textile and paper industries	Das et al. 2012
	Enzyme production with slaughterhouse effluent and cabbage waste mixture	Ramakodi et al. 2020
Carrot, red cabbage, red beet by-products	Biocatalyst for pharmaceutically important molecules, agrochemicals, flavours, and asymmetric chiral ligands	Vandenberghe et al. 2013
Red cabbage outer leaves	Colourant for textile industry	Priyadarshini et al. 2021
Red beet peel	Betalains for colour industry	Fernando et al. 2021, Popescu et al. 2021

Electrical uses

Electrical products are a marginally examined product sector for the vegetable by-products. However, Ahmed et al. (2018) and Hoang et al. (2019) found carrot waste to be suitable for energy storage products (Table 9). Of the materials examined, Mannarmannan and Biswas (2021) found carrot peel extract to be the best for preparing copper oxide nanoparticles with antibacterial properties.

Table 9. Studies of carrot, cabbage, and red beet by-products in electrical use

By-products as raw materials	Active component or structure and product or application examples	Reference
Rotten carrots and other vegetable by-products	Porous activated carbon-based electrode for energy storage applications	Ahmed et al. 2018
Carrot discards	Precursor for Ni/P-doped carbon composite electrocatalyst for e.g. batteries, fuel cells, and electrocatalytic water splitting	Hoang et al. 2019
Carrot peel	Synthesis of Cu_2O nanoparticles with antibacterial properties from carrot peel extract	Mannarmannan and Biswas 2021
Red beet discards	Single-crystalline gold (Au) nanoplates from extract for use, e.g., in catalysis, photonics, biosensing, electronics, or nanomedicines	Deokar and Ingale 2018
Cabbage outer leaves	Carbon aerogel for supercapacitors and adsorbent for oil/water separation	Cai et al. 2017

Discussion

Valorization options

This review summarizes the literature on valorization options for by-products of carrot, red beet, and cabbage that are important vegetables in northern climates. The review showed that there is no single answer about the best use for the by-products of the vegetables under focus. The Waste Framework Directive sets the basic concepts and definitions related to waste management. Preventing waste is the preferred option, and preparing by-products for re-use, recycling, recovery, and sending waste to landfill should be the last options (EU 2008). Vegetable wastes are rich sources of vitamins and minerals for producing high-value compounds or metabolites (Yadav et al. 2023). Studies on various valorization options provide valuable insights into the potential uses of vegetable by-products for different-sized production companies. Some potential for using the by-products of carrot, red beet, and cabbage in food applications was observed. There were only a few studies about these by-products in medicine and cosmetics, and food and pharmaceutical uses were often lumped together. These by-products or discards are used as such in animal feed, but quality upgrading for different animal species appeared positive in several studies. According to Ajila et al. (2012), the production of animal feed from agro-residues could be one of the most suitable technologies for finding an effective way to attain income by the agro-community and for the better management of environmental pollution. On the other hand, Esparza et al. (2020) mentioned bioactive compounds, enzymes, exopolysaccharides, bioplastics, and biofuels as the most promising options for valorization. In addition to food applications, Rapa et al. (2024) mentioned biogas and organic fertilizers, animal feed and innovative food packaging, and construction and water purification materials as potential applications.

Particularly, cabbage was promising for biogas production via anaerobic digestion. By-products, particularly of carrot and cabbage, appeared suitable for producing biochar that can be used as a fertilizer or to remove contaminants, such as heavy metals or phosphorus, from the environment. Carrot or cabbage by-products in the form of activated carbon were common in wastewater purification. Both activated carbon, lignocellulose, and pectin from the by-products were mostly potential as biosorbents. Composting of cabbage for soil amendment was mostly promising, while studies on other treatments for soil improvement and biopesticides were few and contradictory. Carrot and red beet by-products had potential in the production of films and packaging materials. Carrot or cabbage wastes showed potential for the production of the enzymes, and red beet also for textile dyes. However, in this case, contradictory results were found too. Some technical valorization options, e.g., electrical products, were examined only in a few studies, in which the by-products were nevertheless found functionally as potential product sectors.

In practice, the most profitable valorization options are those related to centralizing the production and capitalizing on economies of scale (Cristobal et al. 2018). For example, the production of flour from vegetable by-products is affordable only if high value-added ingredients and products are developed (Ratti 2001). Economic profitability was not the focus of many of the studies reviewed. Technical feasibility, including pre-treatment, extraction and production methods, is highly important for both production technical and economic reasons. Sustainable recovery technologies eliminate harmful effects compared to conventional technologies (Czubaszek 2022). Green extraction methods in the separation of various bioactive compounds from vegetable by-products correspond to the aims of the circularity of resources and sustainability (Rapa et al. 2024). Many studies exploit technologies such as ultrasounds, microwaves, high pressure, and supercritical fluid processing, for by-product processing. However, these incur huge investment and maintenance costs, along with requiring specialized know-how and production plants (Galanakis 2013). The costs are high even when using technologies characterized by a high industrial maturity level, e.g., air-drying (Ferreira et al. 2015). For example, biofuel applications (approximately 186–372 €/tonne biomass) create more value compared to generating electricity (approximately 56–139 €/tonne biomass) and cattle feed (65–186 €/tonne biomass), but the turnover that could be generated by high-value biochemicals is much higher and estimated to be around 930 €/tonne biomass (Tuck et al. 2012). An accurate cost-benefit analysis should be performed to evaluate the environmental and economic sustainability of the proposed vegetable waste valorization strategies (Coelho et al. 2020).

In this review, valorization options were examined, including all by-product sources. However, industrial by-products and wastes are typically more homogeneous and constant in composition than those generated during the consumption phase, which makes them a more attractive option for valorization (Fava et al. 2015, Rao et al. 2021). In addition, the type of by-product affects its properties and thus its use potential, although the part of the vegetable examined as a by-product was not specified in all studies, or vegetable waste was examined as a whole. For example, red beet has a high antioxidant capacity (Porto Dalla Costa et al. 2017, Šeremet et al. 2020, Salamatullah et al. 2021, Zin and Bánvölgyi 2021, El-Beltagi et al. 2022), but the composition is not equal in all parts of the vegetable (Kujala et al. 2000). In Zin and Bánvölgyi (2022), the contents of betalains, phenolics, and flavonoids were also the highest in red beet peel, followed by the flesh and stalk. Based on this review, industrial-scale studies are needed to confirm the utilization of valuable components of vegetable by-products.

Challenges in valorization of by-products

According to Socas-Rodriguez et al. (2021), the valorization of food by-products is challenging for several reasons: the different stabilities of the added-value components during processing, the technological difficulty in large-scale production, the low energy efficiency and high costs of conventional extraction processes, and the use of non-food-grade solvents during conventional extraction processes. A central challenge is the perishable nature and heterogeneity of vegetable by-products and logistical arrangements (Esparza et al. 2020). The presence of moisture is connected to the stability and microbiological safety of food products (San Martin et al. 2016). For this reason, many processes applied for the valorization of food waste involve a drying step in which the water content is preferably reduced to less than 12% (Gomes et al. 2020, Iriondo-DeHond et al. 2018, Ribeiro et al. 2020, San Martin et al. 2016). Drying consumes a lot of energy, and in the northern countries, it is expensive when solar energy is limited.

Finding reference values that allow determining the suitability of the obtained by-products for certain uses has been difficult, as no legislation has specifically been established in this regard. The transfer of contaminants from the raw material to the valorized product must be evaluated, along with the generation of new hazardous substances or their enrichment during food by-product processing (Socas-Rodriguez et al. 2021). The lack of regulation creates risks for the valorization of many potentially useful by-products from the agro-food industry. This problem brings about the necessity for determining specific regulations for food by-product valorization and safety (Socas-Rodriguez et al. 2021). By-products from organic farming lack residual pesticides or potentially toxic chemicals (Barbulova et al. 2015), which is a benefit for food applications.

Environmental sustainability

The strategy of the Circular Economy Action Plan is to use waste material and energy as inputs for other industrial processes or as regenerative resources for nature (EU 2020). However, when developing the processing chains of vegetables, waste prevention should also be emphasized. The US Environmental Protection Agency's waste hierarchy ranks waste prevention as the most preferable option, and energy recovery as a less preferable strategy of waste management compared to others (EPA 2023).

Vegetable by-products are of lower consequence to the environment compared to some other waste streams, but their leachates and CH_4 emissions still present a risk (Misi and Foster 2002). According to the Food and Agriculture Organization of the United Nations (FAO), food loss and waste is the second-highest cause of greenhouse gas emissions. Statistically, 1.3 billion tonnes of wasted food caused approximately 4.4 gigatonnes of greenhouse gas emissions (FAO 2015). Vegetable by-products obtained from the food bioprocessing industry remain a major surplus, leading to environmental pollution (FAO 2013). The global carbon footprint of food loss and waste, excluding emissions from land use change, is estimated at 3.3 gigatonnes of CO_2 equivalent, while surface and groundwater resource use is attributable to circa 250 km^3 of food lost or wasted, and almost 1.4 billion hectares are used to produce food that is later lost or wasted (FAO 2013). Approximately 40 823 kg of carrot rejects and waste destined for landfills released 6 988 kg of CH_4, equivalent to 174 710 kg of CO_2 (Kaur et al. 2022a). Improper disposal of vegetable waste and combustion leads to environmental pollution with the release of dioxins. Landfilling with vegetable wastes also causes water and air pollution and leads to CH_4 gas emissions (ElMekawy et al. 2015).

Implementing non-thermal technologies, adding sustainable solvents and safer materials, and possessing GRAS (Generally Recognized As Safe) status are strongly recommended. Conducting integral investigations that include recovery protocols and preservation assays is necessary to ensure industrial exploitation and sustainability of the final product (Galanakis et al. 2015). Innovative valorization strategies have been shown to maximize the economic performance of the considered system (Plazzotta et al. 2020). A holistic approach is needed for utilizing vegetable by-products, including environmental aspects, technical feasibility, processing techniques, and economic profitability. Holistic examination of the sustainability of by-products, including different processing techniques, is also needed, particularly via life cycle assessment.

Conclusions

This literature review showed that plenty of valorization ideas in a wide variety of applications, including technical applications, have been examined for carrot, cabbage, and red beet by-products. Thus, there is not a single best use for the by-products of the vegetables under focus. Food applications were the most examined product sector. More studies for the food sector were found concerning carrots and red beets when compared to cabbage. Most studies indicated at least some potential for these by-products in food use. Fewer studies focused on pharmaceuticals and cosmetics. Vegetable by-products are often used untreated for animal feed, but valorization studies for several animal groups were also found. Technical applications as valorization targets included biosorbents (mostly based on activated carbon), composites and films (mostly food packages), energy products (mostly biogas but also bioethanol and biodiesel), soil amendments and pesticides, enzymes, dyes and biosurfactants, and electrical applications.

From an economic point of view, balancing between the amount, quality, logistics, and processing technologies of the by-products is a key issue. According to the literature, high-value biochemicals may be among the most profitable valorization options. To handle the significant amounts of by-product biomass created, tailored nutraceutical or feed additive products, bioplastics, or biofuels might also be realistic options on a large scale. However, since most of the studies reviewed were of laboratory scale, research on an industrial scale is needed.

Food loss and waste are a significant cause of greenhouse gas emissions. Concerning environmental sustainability, waste prevention is the primary option. Vegetable waste contains valuable biomass and nutrients, and the valorization of vegetable by-products can result in relative environmental benefits. To decrease emissions from the treatment of vegetable by-products, non-thermal technologies and sustainable solvents should be considered.

The transformation of vegetable by-products into new products with maximum added value aligns with the precepts of the circular economy and the desire for natural ingredients. Many studies on the use of vegetable residues of interest in northern climates were reviewed from the viewpoints of valorization, but it is important to increase the scope of such studies, interrelating many other aspects that have a direct impact on the amount, type, and management of the generated residues. More studies about the economic and environmental aspects of utilizing vegetable by-products are needed. Many product ideas and research results exist, and these could be used, for example, in creating a company's by-product utilization strategy.

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