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Root vegetable side streams as sources of functional ingredients for food, nutraceutical and pharmaceutical applications: The current status and future prospects

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ABSTRACT

Background: Rapid growth of global population leads to an increase in food demand and food processing. Enormous amounts of root vegetable side streams (RVSS) are generated annually. Despite being a rich source of nutrients and bioactive components, RVSS are used as animal feeds or disposed in landfills. A large number of studies have been carried out to explore the potential of food application and value-addition to RVSS. However, the literature and research findings are scattered. This review aims to systematically examine the data in the literature as the current state-of-the-art in order to support future research for valorizing RVSS.
Scope and approach: This paper carries out a comprehensive review of the scientific literature on valorization of RVSS in terms of processing technologies, high-value compounds, biological activities, and potential application in food, nutraceutical, and pharmaceutical products. The main challenges and development perspectives of utilizing RVSS are also discussed.
Key findings and conclusions: Fractions enriched with proteins, fibers and bioactive compounds can be obtained from RVSS by conventional and green extraction methods. Incorporating proteins from the leaves, and fibers from the peels and pomaces enhanced nutritional values and the functionality of food products. Phenolic compounds, carotenoids, and other bioactive compounds in RVSS presented high antioxidant, antimicrobial, hypoglycemic and anticancer activities, showing good potential in the application of nutraceuticals and pharmaceuticals. Future research should focus on in-depth understanding of RVSS composition and the bioaccessibility of the beneficial components. Safety assessment of the RVSS-derived ingredients/fraction should also be further explored.

1. Introduction

According to Food and Agriculture Organization of the United Nations (FAO) forecasts, the world population will reach 9 billion by 2050, which requires a 70% rise in food supply (FAO, 2009). Root vegetables play important roles in food consumption and have a large global output reaching over 846 million tonnes in 2019 (FAO, 2021). Inevitably, enormous volumes of side streams of root vegetables (RVSS) are produced annually, of which the total amount is up to 50% of total yields of the root vegetables (Righetti et al., 2019). These side streams are generated from both the primary production (mostly as leaves and low-quality roots as rejects) and food industrial processing (peels, pomace, and pulps).

Although these RVSS are commonly applied as animal feeds or disposed in landfill, they have great potential as nutrient-fortified and/or bioactive ingredients in human foods due to their richness in valuable compounds (Javed et al., 2019). Nutritionally, RVSS are rich sources of proteins (7–25%, dry wt. basis), dietary fibers (7–53%), starch (25–37%), and pectin (14–25%) (Asadi & Khan, 2021; Boruczkowska et al., 2020; Chantaro et al., 2008; Javed et al., 2019; Leite et al., 2011; Pérez-Chabela et al., 2021; Puligundla & Mok, 2021; Sahni & Shere, 2017; Šeremet et al., 2020; Titcomb, Kaeppler, Cates, et al., 2019; Tiwari et al., 2021; Yang et al., 2018). Nowadays, the market for plant-based proteins and dietary fibers expands rapidly. The replacement of animal proteins with plant-based proteins gain increasing attention, since

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Abbreviations: RVSS, Root vegetable side streams.
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over consumption of meat is positively associated with the risks of carcinogenic or cardiovascular disease (Qin et al., 2022). Dietary fibers, fermented in the colon, can modulate gut microbiota by inhibiting the growth population of pathogenic bacteria and promote gut health. The evidence demonstrated that the risks of human metabolic diseases such as diabetes and intestinal diseases can be reduced by the consumption of dietary fibers (Zuñiga-Martínez et al., 2022). These beneficial properties of plant-based proteins and dietary fibers provoke the increase in market demands, with the compound annual growth rate (CAGR) expected to be 12% and 13% by 2027, respectively (Poutanen et al., 2022). Due to the limitation of arable land area and yields of vegetable crops, it is a huge challenge to obtain plant-based compounds only from vegetable crops. In fact, RVSS have shown the potential of being better sources of beneficial components. For instance, root vegetable leaves have higher content in proteins compared to the root parts, whereas their peels and pomace are a good source of dietary fibers (Akyüz & Ersus, 2021; Boruczkowska et al., 2020). Theoretically, each tonne of root vegetable leaves has 250 kg proteins and 100–500 kg dietary fibers are contained in 1 tonne of root vegetable pulp/pomace/peels (Abdo et al., 2021; Chantaro et al., 2008; Goneim et al., 2011). Additionally, abundant bioactive components, such as polyphenols, carotenoids, and betalains are found in RVSS as well. These compounds have shown great potential in antioxidative and antimicrobial capacities, as well as reducing the risk of cardiovascular disease, cancers and diabetes (El-Beltagi et al., 2022; Tiwari et al., 2022). Valorization of RVSS into high value products will support the sustainability and resilience of the global food system.

In this review article, we will provide a comprehensive review and critical assessment on current research regarding the RVSS valorization in terms of pre-treatment for increasing extraction efficiency, high value-added compounds for nutraceutical and pharmaceutical purposes, the biological activities of the valuable compounds and the current application of RVSS in foods (Fig. 1). The potential challenges and future development perspectives of each RVSS source and utilization procedures are also discussed. The aim of this review is to summarize the current studies and innovations on RVSS and identify the key challenges from both aspects of phytochemical analysis and practical application. This review will provide important knowledge for both the academia and industry to obtain a better understanding of RVSS and to promote the sustainable utilization of natural resources.

2. Root vegetable side streams

Potato, carrot, sugar beet and beetroot are commonly consumed root vegetables in human daily diet. Potato (*Solanum tuberosum* L.) is the top crop in global food processing sectors. In 2020, the global yield of potato was 359 million tonnes, with large productions from China, India and Ukraine (FAO, 2021). Carrot (*Dacus carota* L.) has a large global output (including turnips) of approximately 41 million tonnes in 2020 (FAOSTAT, 2021), above 45% of which is produced in China (Encalada et al., 2019). Sugar beet (*Beta vulgaris* L. var. altissima) is known as one of the sources of producing white sugar, the yield of which reached approximately 253 million tonnes globally in 2020 (FAOSTAT, 2021). Russia, France, Germany and the United States are the top countries with high sugar beet production (FAO, 2021). Beetroot (*Beta vulgaris* L. var. conditiva) is a traditional vegetable in many countries. Global production of beetroot reached to approximately 270 million tonnes annually (Chhikara et al., 2019). Global large producers of beetroot include France, Russia, Germany and United States (Chhikara et al., 2019). Tables 1–4 listed the detailed information of the leaves, peels, pomace, pulps, rejects and discards of these root vegetables, which were commonly generated in agro-industrial processing.

2.1. Peels

During industrial processing, up to 11–50% of the root vegetables end as peels (El-Beltagi et al., 2022; Muthurajan et al., 2021; Taher et al., 2017). Root vegetable peels contain starch (25%, dry wt.), non-starch polysaccharide (30%, dry wt.), proteins (10–18%, dry wt.), dietary fibers (15–45%, dry wt.), lignin (20%, dry wt.), lipids (1–2%, dry wt.) and rich in carotenoids and polyphenols (Javed et al., 2019; Pérez-Chabela et al., 2021). Valuable compounds with health-promoting functions in root vegetable peels have been studied in recent research. Adequate

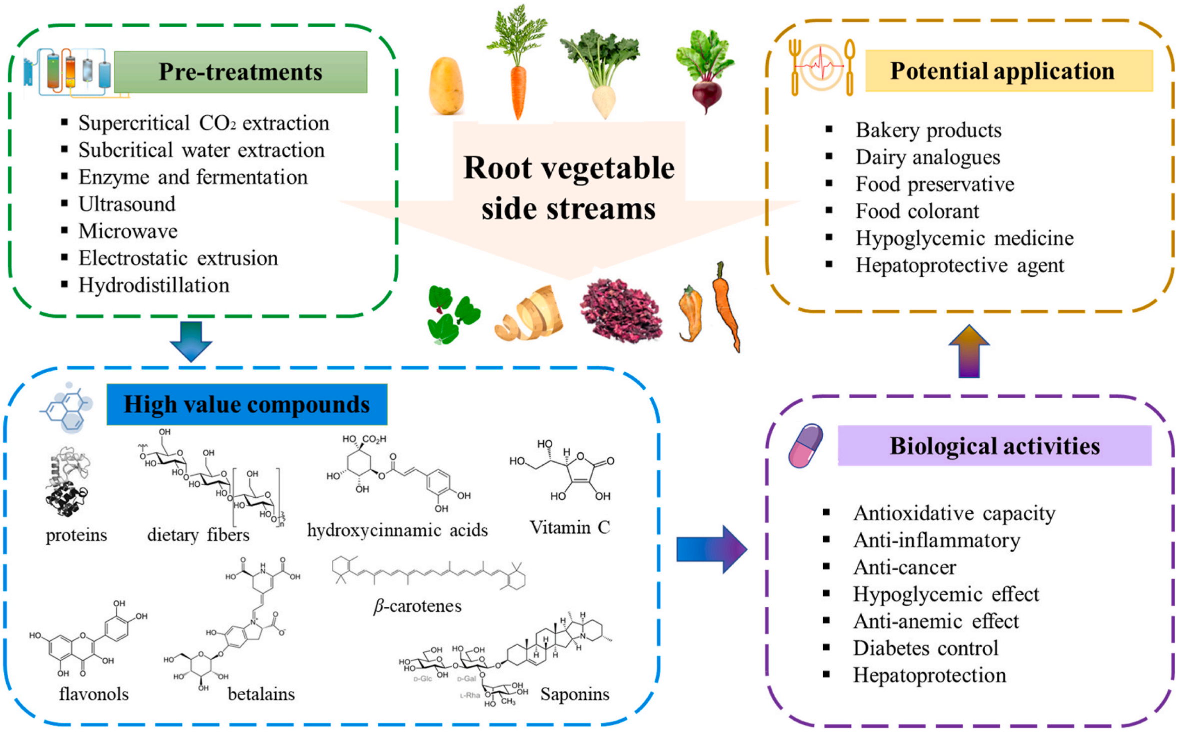

Fig. 1. Pre-treatments adapted in current studies on valorizing nutrients and bioactive compounds in RVSS, and their biological activities and potential applications.

Table 1

Incorporation of potato side streams in foods, nutraceutical and pharmaceutical applications [a].

Extraction/Pre-treatment/ technique	High value-added compounds	Biological activity	Food application	Other findings	Optimized experimental condition/incorporated contents	Sensorial evaluation	Reference
Potato peels							
air dried, ground, 3D printing	↑ protein, ↑ fiber	–	noodle	WF/fine-PP (60:40) possesses good pasting characteristics with better flowability and printability.	40% potato peel powder of whole wheat flour base	↑ overall acceptability, ↓ brightness, ↑ cooking time, ↑ hardness, ↓ appearance	Muthurajan et al. (2021)
oven dried, ground, response surface methodology	↑ fiber, ↓ fat	–	snack	–	2% potato peel powder in the formula	↑ hardness, browning index	Azizi et al. (2021)
oven dried, ground	↑ dietary fiber, ↑ polyphenols	prebiotic capacity	yogurt	–	2% potato peel flour in 1 L of rehydrated skim milk	↓ syneresis, ↑ viscosity, ↓ color, ~ acceptation score, ~ flavor	Pérez-Chabela et al. (2021)
oven dried, ground	↑ protein, ↑ fiber	–	cake	↑ tenacity, ↑ extensibility	5% potato peel powder of wheat flour base	↑ sensory quality, ↓ darkness, ↑ texture, ~ overall acceptability	Ben Jeddou et al. (2017)
commercial potato peel fiber	↑ fiber	–	bread	↑ bread texture, ↓ bread staling	0.4% potato peel fiber of flour basis	–	Curti et al. (2016)
freeze dried, ground to fine powders	inhibition rate of *Bacillus cereus* growth	↑ antimicrobial capacity	cooked rice	↓ *Bacillus cereus* germination and outgrowth during cooking	the powder mixed with rice at 10% (w/w)	–	Juneja et al. (2018)
freeze dried, ground	↑ phenolics, ↑ anthocyanins	↑ antioxidative capacity	natural antioxidant	phenolic content: potato peel > fresh potato; anthocyanin content: potato peel > fresh potato; antioxidative capacity: potato peel > fresh potato	–	–	Albishi et al. (2013)
Potato pulp							
commercially dried, ground	pectic polysaccharide	–	acidified milk drinks	↓ serum separation, ↓ particle size distribution, ↓ viscosity, ↑ shelf life	0.5% potato pulp pectic polysaccharide	–	Sun et al. (2020)
commercially dried	↑ dietary fiber	–	shortcrust pastry cookies	–	40% dried potato pulp of flour basis	~ crispness and hardness, ↓ color saturation	Boruczkowska et al. (2020)
oven dried and cut into 5 mm in length; extruded	–	–	spaghetti	↓ water absorption index, ↓ water solubility index, ↑ cooking characteristics, ↓ optimum cooking time, ↓ loss of solids to water, ↑ yield	combination of 65% dried potato pulp, 10% extruded potato pulp and 25% amaranth flour	↑ color	Bastos et al. (2016)
ground, extracted by McIlvaine buffer	↑ proteins	↑ antioxidative capacity	pharmaceutical application	Potato pulp extracts retained a high peroxidase activity during long-term storage.	–	–	Kurnik et al. (2018)
oven dried, ground, extracted by HCl, H_2SO_4, HNO_3, citric acid and acetic acid	↑ pectin, ↑ protein	–	emulsifier	↑ emulsifying activity, ↑ emulsion stability	Highest pectin yield by citric acid extraction and highest protein content by acetic acid extraction.	–	Yang et al. (2018)

[a] The symbols of ↑, ↓, ~ stand for the meaning of increasing, decreasing and equal, respectively.

Table 2
Incorporation of carrot side streams in foods, nutraceutical and pharmaceutical applications [a].

Extraction/Pre-treatment/technique	High value-added compounds	Biological activity	Food application	Other findings	Optimized experimental condition/incorporated contents	Sensorial evaluation	Reference
Carrot leaves							
paste	↑ protein, ↑ fat, ↑ dietary fiber, ↑ Calcium, ↑ Iron, ↑ β-carotene	–	pasta	10% substitution by fresh carrot leaves paste in the flour showed better results in enriching proteins, crude fibers and calcium in the pasta than by the same proportion substitution of beetroot paste.	10% carrot leaves paste of the flour base	–	Veena et al. (2019)
ground	↑ PUFA/SFA, ↑ phenolics	↑ antioxidative capacity	pasta	↓ cooking time, ↓ weight increase	5% carrot leaves powder, 5% oregano leaves powder or 10% only carrot leaves powder of the flour base	adequate sensorial characteristics of color, texture, aroma, flavor	Boroski et al. (2011)
oven dried, extracted by acetone	↑ phenolic compounds, ↑ minerals	↑ antioxidative capacity	natural antioxidant	↑ storage time of sunflower oil, ↑ minerals (K, Ca, P, Fe, Zn)	0.1% carrot leaves acetone extract	–	Goneim et al. (2011)
hydrodistillation	essential oils	↑ antibacterial activity	essential oils	good aromatic property	hydrodistillation for 4 h	–	Chiboub et al. (2019)
oven dried, ground	↑ xanthophyll carotenoids	–	hen feed	↑ egg yolk color	0.4% in basal feed	–	Titcomb, Kaeppler, Cates, et al. (2019)
dried, ground	↑ provitamin A carotenoids	–	animal feed	maintain vitamin A status	15–50% of animal feeds	–	Titcomb, Kaeppler, Cook, et al. (2019)
freeze dried, ground, subcritical water extraction	↑ polyphenols, ↑ luteolin	antioxidative, anti-inflammatory antibacterial capacity	nutrition source	–	extracted at 210 °C for 113.5 min	–	Song et al. (2018)
oven dried, extracted by 50% ethanol with 0.05 M ortho-phosphoric acid	phenolic compounds	antioxidative capacity	natural antioxidant	kaempferol-malonyl-glucoside, quercetin-3-O-malonyl-glucoside A, rutin, cynarin, caffeic acid and neo-chlorogenic acid were associated with antioxidative capacity	ethanol/water (50/50 v/v) containing 0.05 M ortho-phosphoric acid	–	Burri et al. (2017)
Carrot peels							
air dried, ground	flavonoids and phenolic compounds	↑ antioxidative, cytotoxic and antimicrobial capacity	medicinal source	–	powdered sample extracted by 80% ethanol at room temperature, shake every 2 h for one day	–	El-Sawi et al. (2022)
oven dried, blanched in hot water, ground	↑ protein, ↑ dietary fiber, ↑ pectin, ~ phenolics, ~ β-carotene	~ antioxidative capacity	nutrition source	↑ IDF:SDF ratio	dry at 60 °C and blanched in hot water at 90 °C for 1 min	–	Chantaro et al. (2008)
water-induced hydrocolloidal complexation	β-carotenes-pectin	↑ antioxidative capacity	nutrition source	high purity and yield of β-carotenes	6% (w/v) of solid loading, 1500 rpm of stirring speed, and 60 min of stirring duration	–	Jayesree et al. (2021)
pan cooking for 15 min, add citric acid to adjust pH to 3.2	↑ flavonoids, ↑ phenolics, ↑ dietary fiber, ↑ fat, ~ minerals, ↓ protein, ↓ Vitamin C	↑ antioxidative capacity	jam	–	1 kg peels, 1 kg sugar and 8 g pectin	second highest lightness of color, lowest sensorial characteristics of taste, odor, mouth feel and appearance	Hussein et al. (2015)
Carrot pomace and pulp							
oven dried, ground	↑ dietary fiber, ↑ protein	–	cake	↑ viscosity, ↑ hardness	5% carrot pomace of rice flour base	↓ taste, ↓ color	Kırbaş et al. (2019)
freeze-dried, ground	↑ anthocyanins, ↑ phenolic acids	↑ antioxidative capacity	cake	Significant increases in total phenolic content and total antioxidative capacity were obtained after simulated gastric and intestinal digestion (up to 5- and 12-fold respectively).	15% carrot pomace of flour base	–	Kamiloglu et al. (2017)

(*continued on next page*)

Table 2 (*continued*)

Extraction/Pre-treatment/technique	High value-added compounds	Biological activity	Food application	Other findings	Optimized experimental condition/incorporated contents	Sensorial evaluation	Reference
oven dried, ground	↑ dietary fiber, ↑ single cell protein, ↑ minerals	–	noodle	↓ cooking time, ↑ swelling index, ↑ cooking yield	20% carrot pomace of flour base	~ sensory properties, except 8% dosage addition	Razzaq et al. (2022)
oven dried, ground	↓ protein, ↓ fat, ↑ crude fiber	–	chicken sausage	↑ cooking yield	3% carrot pomace	↓ color, ↓ flavor, ↓ texture, ↓ juiciness, ↓ tenderness as carrot pomace proportion increased	Yadav et al. (2018)
freeze-dried, ground, extracted by flaxseed oil	↑ fat, ↑ protein, ↑ carotenoids	↑ antioxidative capacity	flavored milk	↑ color	10% emulsion of carotenoids from carrot pomace	↑ color & appearance, ↓ odor, ↓ taste, ↓ mouthfeel, ↓ overall acceptability	Tiwari et al. (2022)
freeze-dried, ground, extracted by supercritical CO_2	–	↑ antioxidative capacity	antioxidant	↑ powder yield, ↓ encapsulation efficiency, ↓ bulk density, ↓ tapped density, ↑ flowability, ↓ oil oxidation	encapsulation pressure of 10 MPa	–	Klettenhammer et al. (2021)
oven dried, ground	↑ dietary fiber	–	pasta	↓ cooking time, ↑ swelling index	10% carrot pomace	↓ appearance, ↓ color, ↓ smell, ↓ taste, ↓ flexibility, ↓ hardness, ↓ general acceptability as carrot pomace proportion increased	Kultys and Moczkowska-Wyrwisz (2022)
oven dried, ground	↓ protein, ↓ fat, ↑ dietary fiber, ↑ carbohydrates	–	yogurt	↑ pH, ↓ shelf life	10% carrot pomace	↑ texture, ~ sensory quality	El-dardiry (2022)
oven dried, ground	↑ protein, ↓ fat, ↑ polyphenols, ↑ flavonoids, ↑ phenolic acids, ↑ flavonols	↑ antioxidative capacity	bread	↑ dough properties	15% carrot pomace	↓ sensory characteristics, ↓ color, ↑ carrot smell	Ziobro et al. (2022)
Carrot rejects							
freeze-dried, ground, extracted by sunflower oil, encapsulated by electrostatic extrusion technique	↑ β-carotene	↑ antioxidative capacity	yogurt	stable microbiological and physico-chemical properties, antihyperglycemic activity, anti-inflammatory activity	2.5% and 5% carrot waste beads	↑ color	Šeregelj et al. (2021)
oven dried, ground	↑ protein, ↑ vitamin C, ↑ fatty acid	–	bread	↑ volume, ↓ density	10% waste blend (50%–50% broccoli and carrot pulp)	–	Zambelli et al. (2017)
thermal treatment	↑ β-carotene	anticarcinogen	food and nutraceutical application	↑ bioaccessibility/bioavailability of β-carotene	–	–	Kaur et al. (2022)
probiotic-fermented, animal experiment	↓ protein, ↓ fat, ↑ carbohydrates, ↓ water-soluble polysaccharide, ↑ acid- and alkali-soluble polysaccharides	↑ hypoglycemic effects	pharmaceutical application	Water-soluble polysaccharide from probiotic-fermented carrot pulps showed better hypoglycemic effects than that in unfermented pulp.	fermented by L. *plantarum* NUC116 at 37 °C for 24 h	–	Wan et al. (2019)

[a] The symbols of ↑, ↓, ~ stand for the meaning of increasing, decreasing and equal, respectively.

daily intake of dietary fiber from beetroot peels may contribute to reducing the risk of chronic health problems such as heart disease, metabolic syndrome, constipation, and cancers (Šeremet et al., 2020). The polyphenols in carrot peels showed positive effects against inflammation, tumor and free radicals (El-Sawi et al., 2022).

Despite rich in nutrients and bioactive compounds, currently, the peels were commonly used as animal feeds (Albishi et al., 2013). Peels are not efficiently utilized since high fiber content in them leads to low digestibility (Table 1). Therefore, potato peels have to be treated prior to use as feed for non-ruminant animals (Javed et al., 2019). The concern of valorizing root vegetable peels as human foods was that organic solvents were widely used to extract high value compounds. For instance, the selective solvents for extracting carotene and pectin in carrot peels commonly included hexane, acetone, methanol and ethanol (Jayesree et al., 2021). Over-consumption of chemical solvents does not only shift burdens to the environment but also limits the application of the extracts in food products. Green extraction methods, such as food-grade enzymatic processing or fermentation have shown advantages in RVSS extraction due to higher extraction yield, higher quality of extract, and low environmental impact (Akyüz & Ersus, 2021).

2.2. Leaves

Leaves represent approximately 20–34% of the total mass of the root vegetables (Grabowska et al., 2012; Tamayo Tenorio, 2017). Carbohydrates (46–71%, dry wt.), proteins (18–25%, dry wt.), dietary fibers (7–36%, dry wt.), lipids (2–5%, dry wt.), bioactive components such as flavonoids, phenolic acids, carotenoid, betalains, chlorophyll, vitamins and a variety of trace elements are commonly found in the leaves of carrot, sugar beet and beetroot (Asadi & Khan, 2021; Leite et al., 2011; Tamayo Tenorio et al., 2016; T. Titcomb, Kaeppler, Cates, et al., 2019; Veena et al., 2019). As shown in Table 2, carrot leaves have abundant phenolic compounds, the content of which is over ten folds higher than that in fresh carrot (Song et al., 2018). Sugar beet leaves are rich in proteins and contain all the essential amino acids, showing great potential as plant-protein source (Akyüz & Ersus, 2021) (Table 3).

Root vegetable leaves have been occasionally used in household cooking (such as salad ingredients). Still, their safety in food application has not been well evaluated (Mazzucotelli et al., 2018). Direct use of these leaves in human diet may cause safety issues due to the presence of chemical contaminants, pesticide residue, or potential pathogens that may threaten consumers' health (Šuk et al., 2021). Therefore, assuring the safety of the leaves is of importance to achieve the valorization for human consumption (Socas-Rodríguez et al., 2021). The evaluation of microbiological safety should involve the assessment of common foodborne pathogens such as *Listeria* spp., *Salmonella enterica* and *Escherichia coli*. Additionally, monitoring RVSS contamination, which may come from crop cultivation, post-harvest storage and processing is also of great importance (Šuk et al., 2021).

In addition to the safety issues, removing the antinutrients in leaves is another challenge. Although beetroot leaves were considered having good therapeutic potential in the treatment of stress-related psychiatric disorders (Sulakhiya et al., 2016), it is not recommended to directly incorporate them into meals after drying and pulverizing (Table 4). The reason is that unprocessed leaves may contain antinutrient such as phytic acid, which can influence the bioavailability of micronutrients and macronutrients at large intake (Bloot et al., 2021).

2.3. Pomace and pulps

Pomace and pulp are side streams of juice pressing (carrot and beetroot), sugar (sugar beet) and starch (potato) industry, with a volume 25–50% by weight of the processed root vegetables (Righetti et al., 2019). They are valuable sources of proteins (4–16%, dry wt.), starch (37%, dry wt.), pectin (17–25%, dry wt.), reducing sugar (8–9%, dry wt.), dietary fibers (11–53%, dry wt.), cellulose (17–25%, dry wt.) and hemicelluloses (14–36%, dry wt.) (Boruczkowska et al., 2020; Puligundla & Mok, 2021; Sahni & Shere, 2017; Tiwari et al., 2021; Yang et al., 2018). They also contain abundant phenolic compounds, betalains, carotenoids, minerals, and vitamins. These nutritional and health-promoting compounds are attributed to the good quality of the pomace and pulps, reducing the risk of cardiovascular disease and promoting gut health (Surbhi et al., 2018).

Yet, for utilizing root vegetable pulps, the challenge lies in the perishability of the materials as their high moisture content (Chen et al., 2020). The moisture content of the pulps can be up to 90%, which may result in rapid growth of undesirable/pathogenic microorganisms (Socas-Rodríguez et al., 2021). Applying a drying process prior to incorporating the pulps into foods is necessary to reduce the water content and to improve the quality of the products (El-Beltagi et al., 2022; Ziobro et al., 2022). Oven-drying and freeze-drying are common methods of decreasing water content in the pomace and pulps, but they both require high thermal energy. Air-drying is acknowledged as an energy-saving approach, which can be applied as an alternative. A comparative study was conducted of drying potato peels using different drying methods (Hossain et al., 2016). A moisture removal of up to 75–78% was achieved by air-drying (at 14 °C for three weeks), vacuum oven-drying (at 70 °C, vacuum of 600 mbar for 16 h) or freeze-drying (at −54 °C, pressure of 0.064 mbar for 72 h). Sugar beet pulp were air dried at ambient temperature for 48 h before pulverizing them into powder, which were further added to cookies as nutrient fortifier (Simić et al., 2021). Yet, the moisture contents of air-dried side streams were not defined in the study. Oven-dried potato pulp, carrot pomace, sugar beet pulp and beetroot pomace reached the moisture contents between 2 and 12% after drying at 40–70 °C for 6–30 h (Bastos et al., 2016; Burri et al., 2017; Kumar et al., 2018; Razzaq et al., 2022). Freeze-drying was conducted for 24 h until the carrot pomace, sugar beet pulp and beetroot pomace reached constant weights (Edelmann et al., 2020; Hidalgo et al., 2018; Kamiloglu et al., 2017).

2.4. Other side streams

Aside from the leaves, peels and pomace, up to 30% of the root vegetables do not enter the food supply chain due to substandard size, irregular shape or mechanical damage (Fradinho et al., 2020). Less than one third of these “low quality” roots, namely rejects and discards, are used as animal feed, while the rest are left in the field (Kaur et al., 2022). Nowadays, valorizing the rejects and discards have raised considerable interest due to the incentive of avoiding food loss and waste. Current research on root vegetable rejects and discards lacks the investigation on their chemical profiles. Additionally, although carrot rejects and discards were added in yogurt and bread formula, sensorial evaluation of the products were not performed (Zambelli et al., 2017; Šeregelj et al., 2021).

3. Pre-treatment

Pre-treatment is the first stage of valorizing RVSS for food application. Higher compound value and yield can be obtained through various pre-treatment and extraction methods. Chemical, physical and biological methods were either solely used or adopted with other modern technologies to increase the extraction efficiency of target compounds (Šeremet et al., 2020).

3.1. Conventional extraction (water, alkaline and acids)

The feasibility of water blanching on producing dietary fiber powder from carrot peels was evaluated (Chantaro et al., 2008). The results suggested that blanching in hot water at 90 °C for 1 min improved the yield of multiple compounds from carrot peels. Except dietary fibers, contents of proteins and pectin were also increased compared to unblanched carrot peels, while total contents of phenolics and carotene,

Table 3

Incorporation of sugar beet side streams in foods, nutraceutical and pharmaceutical applications [a].

Extraction/Pre-treatment/ technique	High value-added compounds	Biological activity	Food application	Other findings	Optimized experimental condition/incorporated contents	Sensorial evaluation	Reference
Sugar beet leaves							
freeze-dried, ground	flavonoids, phenolic acids	antioxidative capacity	salad	–	methanol/water (80/20 v/v)	–	Mazzucotelli et al. (2018)
enzyme mixture (contains polygalacturonase, pectinesterase and pectin *trans*-eliminase, hemicellulase, and cellulase	↑ protein	–	plant protein concentrate	↑ protein solubility	temperature 54.25 °C, 81.35 min, and solvent/solid ratio of 27.65 mL/g	–	Akyüz and Ersus (2021)
pH shifting, ultrafiltration	↑ protein	–	RuBisCO protein isolate	↑ protein solubility, ↑ emulsion, ↑ gelling	mixed with sodium metabisulfite and $CaCl_2 \cdot 2H_2O$, pH 6.8, kept at 50 °C in 15 min, cool down and ultrafiltration	–	Martin et al. (2019)
animal experiment	polyphenols	antioxidative capacity, anti-hepatotoxic activity	pharmaceutical application	–	ethanol/water (70:30 v/v), concentrated under reduced pressure at 45 °C	–	El-Gengaihi et al. (2016)
Sugar beet peels							
distilled water extract and then frozen	↓ free fatty acids	antioxidative capacity	preservative	↑ shelf life, ↑ quality of rainbow trout, ↓ volatile basic nitrogen, ↓ peroxide value	0.1% peel extracts in ice, fish-to-ice ratio 1:1 (w/w)	↓ flavor with storage time	Yavuzer et al. (2020)
freeze-dried, ground	phenolic compounds	antioxidative capacity	antioxidant	Sugar beet peel potently scavenged nitric oxide and DPPH free radicals, exhibited the highest reducing power, the highest ion-chelating activity for cupric and ferrous ions.	defatted, extracted by methanol/ethanol using sonication for 4 h	–	Arjeh et al. (2022)
Sugar beet pulp							
extracted by heated water, bleached in alkaline hydrogen peroxide	↑ pectin, ↑ protein, ↓ fat, ↑ dietary fibers	–	muffin	↑ texture, ↑ appearance, ↓ hardness, ↑ cohesiveness, ↑ gumminess, ↑springiness, ↑ chewiness, ↓ color, ↓ energy, ↓ porous	1% depectinized fiber of flour base	↓ flavor with higher fiber content	Saeidy et al. (2022)
extruded, air dried	↑ proteins, ↓ fat, ↑ dietary fiber	–	cookie	↓ moisture	up to 15% sugar beet pulp extrudate	↓ color, ↓ hardness, ↑ graininess, ↓ appearance	Simić et al. (2021)
oven dried, ground	phenolic acids	↑ antioxidative capacity	antioxidant	↓ peroxide value	200 ppm (0.02%) sugar beet pulp extract	–	Mohdaly et al. (2010)
freeze-dried, ground	saponins	–	emulsifier	Sugar beet pulp contained low amounts of sugar and high amounts of saponins.	extracted by methanol/water (70:30 v/v) for 30 min	Sugar beet pulp saponins had much less intense on bitter off-taste sensation.	Edelmann et al. (2020)
dried, ground	endo-polygalacturonase	–	pectinase production	The highest activity of endo-polygalacuronase was obtained by using A. *niger* AUMC 4156 and P. *oxalicum* AUMC 4153.	2–3% sugar beet pulp	–	Almowallad et al. (2022)
dried, treated by steam explosion	pectin, cellulose, arabinose	–	pharmaceutical application	l-arabinose from sugar beet pulp was converted into L-gluco-heptulose using mutant transketolase, which had potential therapeutic applications in hypoglycaemia and cancer.	–	–	Cárdenas-Fernández et al. (2017)

[a] The symbols of ↑, ↓, ~ stand for the meaning of increasing, decreasing and equal, respectively.

antioxidative activity were not significantly influenced. It also indicated that improved water retention and swelling capacities by blanching enhanced the potential of the fiber powder in food application. Water-induced extraction was also applicable for recovering complexation of carotene-pectin hydrocolloid from carrot peels (Jayesree et al., 2021). In comparison to the conventional solvent extraction using methanol, hexane and acetone, the operation steps in the water-induced extraction were significantly simplified. Extraction condition optimized by response surface methodology, the maximum recovery yield and purity of β-carotenes were 1.2 mg/100 g (fresh wt. basis) and 96% respectively, with improved antioxidative activity. Except water, flaxseed oil was used as a green solvent for carotenoids extraction from carrot pomace (Tiwari et al., 2022). The result indicated that the emulsion of extracted carotenoids was stable over a range of pH, temperature and ionic strength for flavored milk development. The carotenoids emulsion improved the color of flavored milk by decreasing its lightness/brightness, presenting potential as natural functional colorant.

Heated water followed by alkaline hydrogen peroxide bleaching were used to remove pectin with the aim to produce depectinized pulp fiber from sugar beet pulp (Saeidy et al., 2022). Depectinized sugar beet fiber contained more protein than untreated fiber. After incorporating the fibers (with or without pectin removed) in muffin formula, their impacts on texture and other sensory properties in muffins were investigated. Muffins with depectinized pulp fiber showed the better texture (least hardness and highest cohesiveness, gumminess, springiness, and chewiness), lighter color, lower energy, and less porous in appearance compared with the pectin-fiber formula. From sensorial aspect, there was no significant difference between these two formulations, but higher fiber content decreased the overall acceptance of the muffins by the panelists. Effects of hydrochloric acid, sulfuric acid, nitric acid, citric acid, and acetic acid on the extraction yield and emulsifying properties of pectin from potato pulp were compared (Yang et al., 2018). The results indicated that the highest pectin yield (14%, fresh wt. basis) was obtained by citric acid extraction while acetic acid extracted from potato pulp contained highest protein content (7%, based on dry potato pulp pectin). Comparable results showed that potato pulp pectin (extracted by HCl) has better emulsifying activity (48%) and emulsion stability (46%) than commercial citrus (45% and 36% respectively) and apple (45% and 19% respectively) pectin as a potential emulsifier in emulsified food products.

Although acidic hydrolysis has been considered as one of the most widely-used methods (Modelska et al., 2017), it is not a good option for recovering components from RVSS. Apart from the high volume of chemical consumption, extreme extraction conditions can lead to compound degradation, and the safety of the extracts is the major concern of the edible products. Milder and green technologies are needed for biorefining RVSS to ensure the quality and the safety of the final products.

3.2. *Innovative green technologies (subcritical, supercritical, enzymatic, ultrasound- and microwave-assisted extraction, extrusion)*

Efficiency of conventional extraction (such as infusion, decoction and maceration) and innovative technologies (such as subcritical water, ultrasound- and microwave-assisted extraction) were compared to recover nutritional and bioactive compounds from beetroot peels (Šeremet et al., 2020). Among all the extraction methods, ultrasound-assisted extraction (30 min) obtained the highest betaxanthin yield (8.6 mg/g dry wt.). The conventional extraction method (decoction at 100 °C for 20 min) produced the highest total phenolic content. The results indicated that beetroot peels can be a promising source of food colorant enriched with nutrients and antioxidative property. Emerging extraction technology - supercritical CO_2 was employed to extract bioactive compounds from carrot pomace (Klettenhammer et al., 2021). With optimized extraction condition (30 MPa and 60 °C with a CO_2 flow rate of 2 L/h for 120 min), the yield of extract achieved 1.4%. By adding carrot pomace extract (0.3%), the oxidative stability of the micro-capsulated linseed oil was improved to 8 times longer than that prepared without adding the extract. Although the antioxidative capacity of the extract was confirmed, the key compounds responsible for the activities are not yet well identified. Novel subcritical water was also proved to be an efficient method for extracting polyphenols, especially luteolin from carrot leaves (Song et al., 2018). The result showed that though the total phenolic content increased along with arising water temperature, the optimized subcritical condition for luteolin was 210 °C for 113.5 min.

Food-grade enzyme mixture (combination of polygalacturonase, pectinesterase, pectin *trans*-eliminase, hemicellulase, and cellulase) was applied to sugar beet leaves to evaluate the viability of producing plant protein concentrate (Akyüz & Ersus, 2021). By using response surface methodology, the highest protein yield (79%) was obtained when the enzymatic extraction was implemented for 81.35 min at 54.25 °C, with solvent/solid ratio of 27.65 mL/g. The color values of high brightness and low yellowness of the isolated protein concentrates made them a promising alternative source for plant proteins in food product application. In another study, gravimetric enzymatic method (α-amylase and protease) was employed to recover dietary fibers from potato peels (Ben Jeddou et al., 2017). Assisting with ultrasonication, hemicellulase potently extracted almost the whole pectin in carrot discards, with the highest yield of pectin-enriched fractions achieving 27% (Encalada et al., 2019). Antioxidants including α- and β-carotenes, lutein, α-tocopherol were co-extracted using this method. The fraction containing multiple ingredients can be a profitable food additive. Cellulase was also applied for retrieving pectin from beetroot by-products (Fissore et al., 2013). The physical properties of the extracted pectin showed potential to be used as food emulsifier.

Extrusion is primarily a thermo-mechanical technique with the advantages of low cost and high productivity. By breaking the cell wall, extrusion releases the intracellular components into the extruded product, improving nutritional quality of the product by increasing the digestibility of proteins and starches and the proportion of soluble dietary fiber (Anoop et al., 2023). As an example, sugar beet pulp were extruded and incorporated in cookie formula by various ratios (Simić et al., 2021). The hardness of the cookies decreased with an increase in extrudate particle size. The nutritional quality of the cookies was improved with addition of the extrudate. The substitution of wheat flour with the extrudates up to 15% did not negatively affect the sensory acceptability of the cookies.

4. High value-added compounds

RVSS contain high value-added compounds, which can contribute to the nutrition enrichment and pharmaceutical benefits (Chhikara et al., 2019). Aside from being the essential nutrient in human diet, proteins recovered from RVSS also showed favorable properties of enzymatic functions and improving food texture (Almowallad et al., 2022). Pectins are widely used in food industry (Sun et al., 2020). Polyphenols, carotenoids, betalains and other bioactive compounds play important roles in foods and pharmaceuticals as natural antioxidant, food additives, anti-inflammatory and anti-cancer agents (Wan et al., 2019).

4.1. *Proteins and polysaccharides*

RVSS are considered as promising sources of plant proteins. RuBisCO protein was extracted from sugar beet leaves using mild treatments and an industrially compatible process (Martin et al., 2019). RuBisCO protein isolate contained 93% crude proteins and the protein solubility was higher than 80% (pH $<$ 4.0 or $>$5.5). Compared to commercial whey protein and soy protein isolates, RuBisCO protein isolate showed better properties of foaming, emulsifying, and gelling, indicating sugar beet leaf-protein isolate to be a good nutritious and functional food ingredient. Despite its versatile properties, the laborious extraction process for RuBisCO can limit its use in food products. In side-stream

Table 4
Incorporation of beetroot side streams in foods, nutraceutical and pharmaceutical applications [a].

Extraction/Pre-treatment/ technique	High value-added compounds	Biological activity	Food application	Other findings	Optimized experimental condition/incorporated contents	Sensorial evaluation	Reference
Beetroot leaves							
blanching, oven dried, ground	↑ protein, ↑ fat, ↑ dietary fiber, ↓ carbohydrate, ↑ phenolics	↑ antioxidative capacity	cookie	↑ moisture, ~ energy value	4.5% dried beetroot leaves powder of flour base	↑ hardness, ↓ color, ↓ texture, ↓ taste, ↓ aroma, ↓ acceptability	Asadi and Khan (2021)
extracted by 80% ethanol	↑ phenolics, ↑ betaxanthins, ↑ betacyanins	↑ antioxidative capacity, ↑ antimicrobial capacity	fruit and vegetable smoothie	↓ microflora, ↑ shelf life	6% beetroot leaves of the smoothie formula	–	Verónica et al. (2020)
oven dried, ground	phenolics	↑ antioxidative capacity	food additive	Different phenolic compounds may counteract oxidation in different ways.	–	–	Burri et al. (2017)
lyophilized, ground	↑ phenolics	↑ antioxidative capacity	pharmaceutical application	↓ LDL-mediated oxidation, ↑ antioxidative protection	100 ppm (0.01%) beetroot leaves extract	–	Da Silva et al. (2020)
air dried, ground	behavioural tests, glutathione level, lipid peroxidation assay, protein estimation	stress-related psychiatric disorders	pharmaceutical application	significant prevention of increase in malondialdehyde and depletion of glutathione	100 and 200 mg/kg mice body weight	–	Sulakhiya et al. (2016)
Beetroot peels							
extracted with MQ water, pasteurized and spray dried after adding maltodextrin	anthocyanins, betalains	–	white currant juice	Betalains showed faster degradation rate than anthocyanins, and mixing these two extracts together even accelerated the degradation of both types of color compounds.	2 g betalain powder per L juice	↑ color, ↑ preference of anthocyanins	Yang et al. (2021)
oven dried, ground	phenolic compounds, flavonoids, betalain	↑ antioxidative capacity	preservative	↓ pH, ↓ thiobarbituric acid	100 mg beetroot peels extract per 100 mL water	↑ color, ↑ texture, ↑ odor, ↑ brightness, ↑ acceptability	El-Beltagi et al. (2022)
air dried, ground, infusion, decoction, maceration, subcritical water extraction, ultrasound- and microwave-assisted extraction	dietary fiber, protein, potassium, phenolic compounds, betalain	↑ antioxidative capacity	food colorant	Beetroot peels contained notable amount of dietary fiber (34%) and rich in protein (18%), dietary fiber (34%) and rich in protein (18%), betacyanin yield (9.8 mg/g) and potassium (41.9 mg/g).	infusion at 80 °C for 30 min	–	Šeremet et al. (2020)
air-dried, ground	betacyanins	biological activity	edible film	Beetroot peels extract had no adverse effects on macromolecular models or $CaCo_2$ and HepG2 human cells lines. The fastest release of betacyanins was observed in the beetroot peels-modified edible films incorporated pumpkin proteins during simulated gastro-intestinal digestion.	19.2 g extract incorporated with 0.2 g pumpkin proteins	–	Šeremet et al. (2022)
Beetroot pomace							
freeze-dried, extracted by ethanol:0.5% acetic acid (83.3:16.7) solution; lyophilized	↑ betacyanins, ↑ polyphenols, ↓ furosine	↑ antioxidative capacity	biscuits	–	10.8% beetroot pomace of microencapsulation	↑ redness, ↓ brightness	Hidalgo et al. (2018)
oven dried, ground	↑ protein, ↑ crude fiber, ↓ carbohydrate, ~ fat	–	cookie	↑ moisture	10% dried beetroot pomace powder of flour base	↑ hardness, ↓ texture with the increasing level of incorporation of beetroot pomace powder	Sahni & Shere (2017)
oven dried, ground, diluted by acidic water (pH 2.5) in 1:15 solid to liquid ratio	↑ phenolics, ↑ betaxanthins, ↑ betacyanins	↑ antioxidative capacity	candy	–	7.81 min blanching time and 9.24% beetroot pomace extract concentration	↑ color, ↑ hardness, ↓ overall acceptance	Kumar et al. (2018)
extracted by using ethanol 70%, methanol 80%, water and dried to powder	↑ lipid, ↑ protein, ↑ fiber, ↑ sugars, ↑ minerals	↑ anti-anemic effect	biscuits	↑ moisture	15% dried beetroot pomace powder of biscuits formula, 90% standard-diet and 10% biscuit containing 15% pomace	↓ color, ↓ texture, ↓ taste, ↓ flavor, ↓ overall acceptance	Abdo et al. (2021)

[a] The symbols of ↑, ↓, ~ stand for the meaning of increasing, decreasing and equal, respectively.

biorefining, it might not be a good option to purify single compound in practical application. Except for the high cost, the main reason is that the extracted compounds will be added into food matrix, which is a mixture of multi-nutrients. On the other hand, single cell protein can be extracted from carrot pomace at reasonable cost for a wide range of applications (Razzaq et al., 2022). The single cell protein (produced through the inoculation of *Saccharomyces cerevisiae*) exhibited good nutritional quality and was incorporated in noodles. Markedly improvement of both nutrition and technological characteristics of the noodles were observed, especially in terms of proteins, fibers and mineral contents. Negative impact on sensory properties did not appear when dosage of the single cell protein was below 8%. Moreover, proteins and enzymes such as peroxidase were extracted from potato pulp (Kurnik et al., 2018). High peroxidase activity of the extract with long-term storage stability confirmed its promising potential in the construction of biosensor and glucometer and in conjugation with antibodies for the purpose of enzyme immunoassays. Endo-polygalacturonase, which is widely used in food industries, was produced by fermentation using sugar beet pulp as sole carbon source (Almowallad et al., 2022). The result showed that the maximal enzyme activities of endo-polygalacuronase were observed by adding 2% and 3% sugar beet pulp under static and shaken cultures, respectively.

Polysaccharides from RVSS raise interest due to their texture-modifying functionality in foods. Pectic polysaccharide extracted from potato pulp was evaluated as a stabilizer in acidified milk drinks (Sun et al., 2020). Comparing to the stabilizing effect of commercial pectin, potato pulp pectic polysaccharide resulted in narrower particle size distribution and lower viscosity of acidified milk drinks, which could effectively prevent casein flocculation and improve the shelf life. However, consumers' overall acceptance of the modified drinks was unknown due to the lack of sensorial evaluation. Soluble pectin and insoluble cellulose fractions were yielded from sugar beet pulp using steam explosion and enzymatic hydrolysis (Cárdenas-Fernández et al., 2017). Additionally, L-arabinose from sugar beet pulp was converted into L-gluco-heptulose using mutant transketolase, which had potential therapeutic applications in treating hypoglycaemia and cancer.

4.2. Bioactive compounds

RVSS are considered as a rich source of phenolic compounds (Ziobro et al., 2022). Regarding sugar beet, peels showed higher biological capacity of antioxidative and chelating activity comparing to the roots due to higher amount of phenolic compounds (Arjeh et al., 2022). The major of which included epicatechin, gallic acid, quercetin-3-O-rutinoside and kaempferol. Furthermore, flavonoids (234 mg/100 g dry wt.) and betalains (535 mg/100 g dry wt.) were extracted from beetroot peel (El-Beltagi et al., 2022). High concentration of total phenolic (832 mg/100 g dry wt.) in the extract contributed to the potent antioxidative activity. The beetroot peel extract with a concentration of 100 mg/100 mL showed superiority of preservative effect on fish fillet, which inhibited thiobarbituric acid increase at the end of 10-day cold storage. Despite the proven antioxidative capacity of RVSS extracts, different phenolic compounds may counteract oxidation in different ways. In carrot leaves, kaempferol-malonyl-glucoside and quercetin-3-O-malonyl-glucoside A were found to be closely associated with ferric reducing ability of plasma (FRAP), whereas rutin, cynarin, caffeic acid and neo-chlorogenic acid were positively correlated with radical scavenging capacity (ABTS) (Burri et al., 2017). On the other side, ABTS showed close association with xylosylvitexin whereas phenolic content was positively related to rutin in beetroot leaves. A comparative study was conducted by using beetroot peels betalains, grape anthocyanins, and their mixtures as colorants in white currant juice (Yang et al., 2021). None of the extracted betalains, anthocyanins and their mixtures were stable during storage. Betalains showed a faster degradation rate than anthocyanins, and mixing these two extracts together even accelerated the degradation of both types of color compounds. Although both compounds can be used as potential natural colorant in food products, the color of anthocyanins (described as 'dark' and 'natural') was preferred over betalains, which the sensory panelists perceived as 'pink' and 'unnatural'.

Dehydrated carrot leaves was fed to laying hens with the purpose to enrich the egg yolk with adequate xanthophyll carotenoids (Titcomb, Kaeppler, Cook, et al., 2019). It indicated that adding carrot leaves in the feed was considered as a cost-effective method to improve the nutrition value of eggs since even low addition dosage of carrot leaves powder (0.4% in basal feed) obtained a 1.6-fold higher carotenoid content in egg yolk than the control (without adding carrot leaves). It can be considered as a promoted method of improving nutrition of poultry, which may ultimately improve the nutrition for humans after consuming the poultry. Another study of Titcomb, Kaeppler, Cates, et al. (2019) focused on the bioconversion of α-and β-carotene in carrot leaves to retinol (a fat-soluble vitamin A) in gerbils by feeding them with carrot leaf-fortified feed. The result indicated that adding carrot leaves to the feed even at low dietary amount (~1% of feed) prevented the vitamin A deficiency (defined as a liver vitamin A concentration <0.1 μmol/g). Therefore, carrot leaves have been recognized for their potential to improve the quality of human diets by increasing the content of provitamin A carotenoids.

Saponins (betavulgaroside I, betavulgaroside III, betavulgaroside VIII, boussingoside A2, 3-O-[β -D-glucopyranosyl-(1 → 2)-(β-D-xylopyranosyl-(1 → 3))-β-D-glucuronopyranosyl]-28-O-β-D-glucopyranosyl-3β-hydroxyolean-12-en-28-oic acid, and betavulgaroside V) were identified in sugar beet pulp (Edelmann et al., 2020). According to the sensory evaluation report, the addition of sugar beet pulp saponins up to the level of 5% (in Evian water) did not cause bitter off-taste. Saponins extracted from sugar beet pulp could be a promising natural emulsifier in the food industry with good foaming property but much less bitter off-taste.

Up to date, proteins, fibers, secondary plant metabolites such as phenolic compounds and carotenoids are the targeted compounds recovered from RVSS, due to their high possibilities of application and health-promoting potentials. However, challenges remain due to the complex compositions of RVSS, the compounds of which belong to various classes with different functions. Therefore, it is of great importance to conduct in-depth study on RVSS, which can be a basis of revealing the synergistic and antagonistic interactions between the added extracts and food matrix. Comprehensive knowledge of each RVSS can provide better understanding of the material, which contributes to selecting the best processing treatments for utilizing them optimally in practical application. Non-targeted multi-omics (proteomics, glycomics and metabolomics) approaches are good options. Although seldomly adapted in the study of RVSS as yet, the feasibility of omics approach has been proven in monitoring chemical profiles of food-processing wastes (Kriisa et al., 2022). With simple extraction procedure and tandem mass spectrometry detection, omics approach simultaneously determine compounds from different groups (such as carbohydrates, peptides, lipids, and secondary metabolites) for overall chemical profiling.

5. Biological activities of the beneficial compounds in RVSS

Increasing attention has focused on utilizing RVSS since they can contribute to human health benefits, including antioxidative, antimicrobial properties, hypoglycemic effect, hepatoprotective effect, gut bacteria modulating, anemia treatment and oxidative stress managing (Sampaio et al., 2020).

5.1. Antioxidative capacity

The extracts of potato peels can be utilized as antioxidants in food preservation since they presented good capacity on restraining lipid peroxidation due to the richness of chlorogenic, caffeic, *p*-coumaric and ferulic acids (Albishi et al., 2013). Jam incorporated by carrot peels was characterized by its high contents of crude fibers (4% dry wt.), phenolics

(87.4 mg/100g dry wt.), total flavonoids (35.9 mg/100g dry wt.) and antioxidative activity (IC_{50} 1.8 μg/mL) comparing to other fruit wastes (Hussein et al., 2015). Although having good color performance (not as dark as banana peel jam), carrot peel jam showed lowest taste and odor scores among all the by-products. The antioxidative capacity of carrot pomace-modified cake and the underlying mechanism of the bioaccessibility of the anthocyanins and phenolic acids after ingestion were investigated by a three-step *in vitro* digestion model (simulated bucal, gastric and intestinal digestion) (Kamiloglu et al., 2017). This study showed that enrichment of cake flour with carrot pomace caused a dose-dependent increasing contents of anthocyanins (72–267 μg/g dry wt.), phenolic acids (49–148 μg/g dry wt.), total phenolics (54–202 mg GAE/100 g dry wt.) and total antioxidative capacity (21–129 to 153–478 mg TE/100 g dry wt.). After simulated digestion, a significant increase in total phenolic content and total antioxidative capacity was observed (up to 5- and 12-fold respectively). Yet, the authors did not provide sensory characteristics of the cake, which are crucial factors to consider balancing the taste and nutrition value in the cake. In addition to the cakes, biscuits were enriched by encapsulated (11% extract in flour) and non-encapsulated (6% and 10% extract in flour) beetroot pomace extract (Hidalgo et al., 2018). The antioxidative property of beetroot pomace-enriched water biscuits was improved since the product had the highest contents of health-beneficial compounds including betanin, isobetanin and total phenolics. The deep redness color of the water biscuits was stable and confirmed the protective effect of microencapsulation during the production process. In a similar study, beetroot leaves were dried, ground and incorporated into cookie formula (Asadi & Khan, 2021). As a result, adding beetroot leaves enhanced contents of moisture, proteins, dietary fibers, fat, phenolic compounds and antioxidative activity of the cookie. Conversely, carbohydrate value was reduced. The authors also determined that substituting wheat flour with 4.5% beetroot leaves received highest sensory acceptance. Nevertheless, beetroot leaves could be employed as a natural source of nutrient and health-benefiting compounds in human daily diet.

The antioxidative activity of carrot waste-fortified yogurt was compared with that of standard yogurt (Šeregelj et al., 2021). Carrot waste from beverage production was encapsulated into beads and carrot waste beads were added to the yogurt by 2.5% and 5%. From the result, encapsulated carotenoids considerably improved the antioxidative activity (4.2–9.4 μmolTE/180 g of yogurt) of the yogurt and provided part of β-carotene recommended to intake daily. The stability and microbiological profile of the fortified yogurts were well-maintained during the storage period. The antioxidative effect of carrot leaves extract was explored to extend the shelf-life of sunflower oil (Goneim et al., 2011). The result indicated that the addition of 0.1% carrot leaves extract was equivalent as the action of 200 ppm of artificial antioxidant TBHQ in delaying oxidative rancidity in 45 days at 63 °C. In another study, the antioxidative capacities of sugar beet pulp extract were compared with commercial antioxidants of BHT, BHA and TBHQ for 72 h after applying them in commercial edible sunflower and soybean oils (Mohdaly et al., 2010). Oils with sugar beet pulp extract at 200 ppm (0.02%) showed higher oxidative stability compared to the oils with antioxidants of BHT and BHA used at their legal limit, but the extract was less effective than the synthetic antioxidant TBHQ. Nevertheless, sugar beet pulp is a potent source of natural antioxidants that could be explored to prevent oxidation of vegetable oils. The antioxidant-rich ginger candy was developed by adding 9% extract of blanched beetroot pomace (Kumar et al., 2018). The formula presented the highest contents of betacyanin (18.8 mg/kg dry wt.) and betaxanthin (12.8 mg/kg dry wt.) with acceptable sensorial properties. Another research studied beetroot pomace betalains in encapsulated form and confirmed their resistance to the action of digestive enzymes as well as remaining stable under gastrointestinal conditions without significant loss in antioxidative properties (Tumbas Šaponjac et al., 2016). Therefore, the utilization of phytochemical rich extract of beetroot pomace might be increased in pharmaceutical industry and applied as functional food additives due to its oxidative stress managing properties.

5.2. Antimicrobial activity

Limited research studied the antimicrobial effect of RVSS. Effective antimicrobial capacity of beet leaves extract was proved on *Listeria innocua*, *E. coli* and *Saccharomyces cerevisiae* (Verónica et al., 2020). After incorporating beet leaves extract (6%) in fruit and vegetable smoothie, smoothie's native microflora was reduced by 1–3 log circles, and the product shelf-life was extended by one week. The antimicrobial capacity of potato peel powder was also studied (Juneja et al., 2018). As a results, the growth of *Bacillus cereus* in cooked rice was inhibited by adding the powder to the rice by weight ratio 1:10. In the authors' opinion, the method can be extended to other food categories such as meat and dairy products, yet, the authors did not investigate the corresponding compounds with antibacterial property in the potato peels. Oils extracted from carrot leaves presented significant antimicrobial effect on five bacterial strains (gram-positive *Staphylococcus aureus* ATCC 6538, *Bacillus subtilis* ATCC 6633, *Bacillus amyloliquefaciens* (clinical strain), and gram-negative *Escherichia coli* ATCC 8739, *Salmo-nella enterica* CIP 8039 bacteria) and the yeast *Candida albicans* (Chiboub et al., 2019). The main constituents of extracted oils were isospathulenol (relative content of 17–39%), followed by caryophyllene oxide (16–33%) and δ-elemene (9–18%). The obtained high-quality oils showed potential to be a good source of natural antimicrobials in food preservation and aromatic agents in flavor industries.

5.3. Other health-promoting properties

Effects of bioactive compounds present in RVSS on human health have also been reported. Potato peel was applied to modify yogurt formula (2% potato peel flour in the formula) as a prebiotic source (Pérez-Chabela et al., 2021). Due to increased contents of dietary fibers and polyphenols, the potential prebiotic capacity of potato peel flour was proved to benefit the gastrointestinal tract health, with no detrimental effect on consumer acceptance. Processed discards and out-graded carrots are rich source of β-carotene, which is a proven anticarcinogen with capacity against life-threatening diseases (Kaur et al., 2022). The antioxidative, cytotoxic and antimicrobial effects of carrot peels extract were confirmed on five different cell lines: breast cancer cell lines (MCF-7), prostate cancer cell lines (PC-3), liver cancer cell lines (HEPG2), colon cancer cell lines (HCT-116) and lung cancer cell lines (A549) (El-Sawi et al., 2022). Since the anti-cancer capacity was linearly correlated with polyphenols, high contents of phenolics (2.3 g/100 g) and flavonoids (2.9 g/100 g) of carrot peels extract showed great potential in developing new therapeutic pharmaceuticals against cancer and microbial infections. The effects of non-fermented carrot pulp and probiotic-fermented carrot pulp on diabetes control were compared (Wan et al., 2019). As reported, the probiotic-fermented carrot pulp had a more beneficial effect in reducing fasting blood glucose than the unfermented pulp. By investigating the fermentation-induced changes in nutritional components, water-soluble polysaccharide from probiotic-fermented carrot pulps showed better hypoglycemic effects than that in unfermented pulp. Sugar beet leaves extract was characterized as a remarkable hepatoprotective agent against carbon tetrachloride induced hepatic damage (El-Gengaihi et al., 2016). By *in vivo* study performed on Wistar rats, the results indicated that polyphenols were attributed to shield the liver from damage caused by hepatotoxins, due to their antioxidative, anti-inflammation and anti-apoptosis qualities. Beetroot leaves extract improved the inhibition of LDL-mediated oxidative effects on endothelial cells *in vitro* model due to high phenolic content (655.8 ppm of gallic acid equivalents) and good antioxidative capacity (3976.5 μM of Trolox equivalents) (Da Silva et al., 2020). This made beetroot leaves a potential adjunct to phytotherapy in the treatment of atherosclerosis. Additionally, beetroot leaves were also proved to have therapeutic potential in the treatment of stress-related psychiatric disorders, including anxiolytic and antidepressant activity on stressed mice (Sulakhiya et al., 2016). Abdo and co-workers (2021) studied the effect of biscuit enriched with beetroot pomace on anemia in rats and revealed the promising role of beetroot pomace extract in anemia treatment and oxidative stress management. With the increasing proportion of beetroot pomace, there was an enhancement in proteins, fibers, calcium, phosphorus and iron. Consuming biscuits containing 15% beetroot pomace (with highest sensorial score) showed anti-anemic effect in rat after 14 days, and minor kidney and liver dysfunction in the anemic groups were recovered in 28 days.

Currently, the challenge lies in the unexplored area of the bioaccessibility of the beneficial components in the extract/powder. Obtaining the knowledge of the metabolic pathway of the beneficial RVSS-derived components in human digestion system is the key for revealing their underlying mechanism and synergistic effect on human health. Examples of such mechanisms include the impact of oligosaccharides and bioactive compounds on the modulation of gut microbial community and the potential link to decreasing the postprandial glycemic response (Zuñiga-Martínez et al., 2022). Similarly, effort should be placed on RVSS-derived bioactive compounds in pharmaceutical applications. For instance, betalains from beetroot peels have been widely investigated by their anti-cancer capacity (Fu et al., 2020). The synergistic effect of betalains and some anti-cancer drugs with higher cytotoxic potency need to be further investigated by *in vitro* and *in vivo* studies.

6. Potential food applications

To date, various studies have focused on recovering valuable compounds in RVSS and investigating their practical application in foods (Makori et al., 2022; Sampaio et al., 2020). By adding RVSS extract/powder, the nutritional and sensorial properties of the products could be improved. Efforts have been made to utilize RVSS in foods such as bakery products, instant fried noodles, pasta, chicken sausage, fish fillet, yogurt and preparation of fiber rich cookies (El-dardiry, 2022; Kamiloglu et al., 2017; Kultys & Moczkowska-Wyrwisz, 2022; Kırbaş et al., 2019; Yadav et al., 2018; Ziobro et al., 2022).

6.1. *Bakery products*

Ben Jeddou et al. (2017) demostrated that by adding potato peel powder to cake formula, the tenacity and extensibility of the dough was improved, though the darkness of the cake increased along with higher substitution amount of the peel powder. The protein/fiber-enriched cake showed good sensorial and antioxidative property by replacing 5% wheat flour with potato peel powder. Kırbaş et al. (2019) illustrated the batter rheology and sensorial acceptance of the cake with different proportions (5%, 10%, and 15%) of carrot pomace supplement. Increased viscosity of batter and hardness of cake were observed with higher addition amount of carrot pomace. The cakes containing carrot pomace received higher contents of dietary fibers and proteins but lower scores in terms of taste, suggesting that a higher percentage of carrot pomace addition reduces the overall acceptability of the product. Zambelli et al. (2017) proved that the addition of 50%–50% carrot pulp and broccoli to dough successfully increased significant amounts of vitamin C (918.6 mg/100 g) and fatty acids (2%) in bread. This result indicated that 10% inclusion of the mixed pulp was sufficient to supply the daily demand of Vitamin C, therefore, increased the commercial value and potential of the pulps as nutrients fortifier. Curti et al. (2016) added commercial potato peel fiber to bread formula (0.4% potato peel fiber of flour base) to test the physical properties of the bread. The results elucidated that the texture of modified bread was softer due to the improved water holding capacity, consequently, bread staling was reduced.

In another study, the addition of potato pulp fortified the dietary fibers in the cookies (Boruczkowska et al., 2020). In the organoleptic test, the addition amount of potato pulp below 40% did not cause any remarkable change in sensorial qualities of the cookies, although it reduced color saturation. Sahni and Shere (2017) evaluated the acceptability of beetroot pomace-modified cookies. Adding beetroot pomace changed both nutritional and sensorial properties of the enriched cookie. The contents of moisture, crude fibers, and proteins increased but carbohydrates decreased with the increasing level of incorporation of beetroot pomace powder. Cookies incorporated with 10% beetroot pomace powder obtained most sensory acceptance due to improved taste and flavor, avoiding the unpleasant darkness of cookies. Furthermore, a snack formula was developed by adding 2% potato peels powder (Azizi et al., 2021). Low fat content (<3 g/30 g snack) and high fiber content (2.5–4.9 g/30 g snack) of the product showed its potential to be a well-accepted potato snack.

6.2. *Noodles and pasta*

Peel wastes obtained from potato processing industries were prepared in instant noodle formula by using 3D printing technology (Muthurajan et al., 2021). By replacing 40% of refined wheat flour with potato peels (optimum formula), the developed noodle contained a notable amount of proteins (11%) and marginally increased fiber content (3%). Dried and extruded potato pulp was introduced into gluten-free pasta formula (Bastos et al., 2016). The combination of dried potato pulp (65%), extruded potato pulp (10%) and amaranth flour (25%) provided pasta with good cooking characteristics. The satisfactory color, short cooking time (less than 3 min) and low loss of solids (4%) confirmed the potential to produce desirable fresh pasta using potato pulp with good physical and sensory qualities similar to commercial products. Veena et al. (2019) used the paste of carrot leaves and beetroot leaves for pasta production. The pastes were added separately to replace 10% of the flour in the formula. Compared to the formula with only wheat flour, the contents of protein and crude fibers were increased by 13–25% and 1.6–2 folds in leaf-derived pasta, respectively. In a simialr study, carrot leaves was dried and milled into powder to make pasta (Boroski et al., 2011). The result indicated that by adding 10% of carrot leaf powder, the content of proteins (40%), lipid quality (PUFA/SFA of 3.7) and antioxidative potential (IC_{50} value of 64.0 μg/mL) of the pasta were improved. This addition ratio successfully balanced the sensorial, nutritional, and technological properties of the pasta.

6.3. *Other foods*

Dried carrot pomace was used as a source of dietary fibers in chicken sausage to replace 3%, 6%, and 9% of the lean meat (Yadav et al., 2018). The chicken sausage containing 6% carrot pomace showed good sensorial acceptability, higher content of dietary fibers and storability up to 15 days at refrigerated temperature. The consumption of 100 g of this chicken sausage can meet 1/7th of daily recommended intake of dietary fibers. Ice made of sugar beet peel and beetroot peel extracts was used as a natural preservative on rainbow trout (Yavuzer et al., 2020). The shelf life of the fish was prolonged to 25 days while fish fillets were preserved by iced sugar beet peel extract and 0.1% beetroot peel extracts in ice improved chemical and sensory quality of rainbow trout.

Leaves of sugar beet along with other eight vegetables were used to prepare salad mixtures (Mazzucotelli et al., 2018). The high content of phenolic compounds (106.6 mg GAE/100 g fresh wt.) and antioxidative capacity of sugar beet leaves indicated great potential to introduce the leaves as part of the healthy diet. Interestingly, functional edible films can be produced by using beetroot peels in combination with different plant proteins such as rice, peanut and pumpkin proteins (Šeremet et al., 2022). Results showed that beetroot peel extract had no adverse effects on macromolecular models or CaCo2 and HepG2 human cells lines. The fastest release of betacyanins was observed in the beetroot peels-modified edible films incorporated with pumpkin proteins during simulated gastrointestinal digestion.

7. Challenges and future prospects

As discussed in Section 2, the utilization of root vegetable leaves, peels, pomace, and pulp as human foods is facing different challenges. Yet, the general problems of valorizing RVSS remain. Future studies are expected to focus on addressing the insufficient know-how on raw materials (chemical profile), adopting viable and efficient pre-treatment approaches (extraction and application), and gaining thorough understanding of bioaccessibility (action mechanism) of the isolated ingredients in foods and pharmaceutical products. Furthermore, more effort is needed on balancing sensorial quality of the products, to increase consumers' acceptance of side stream-modified foods (Fig. 2).

To improve the storage stability of RVSS (Chen et al., 2020), mechanical pressing is recommended as a dehydration process. The dry mass contents in pressed vegetable pulps increased from 6-12% to 18–30% as a result of the mechanical squeezing of water (Ptak et al., 2022). Nevertheless, the fresh-pressed pulp should be used within a few days to prevent spoilage. Additionally, high-moisture RVSS can be applied with a mixture of other dry agricultural by-products such as hulls and straw, in order to balance the water content while alleviating high cost of dehydration.

Green extraction methods gain increasing attention due to the pressure of environment and the goal of sustainably utilizing nature sources. Extraction kinetics can be improved by adopting innovative extraction methods such as supercritical CO_2 extraction and subcritical water extraction combined with ultrasound and microwave. More efforts are required from scientific researchers on establishing efficient extraction methods at reasonable cost. In the extraction process, nutrient yields are optimized while anti-nutrients (such as oxalates, tannins and phytates) are removed (Bloot et al., 2021).

Little work has been done to explore the bioaccessibility of the beneficial components in the extract/powder. This leads to a huge research gap of the underlying mechanism and synergistic effect of the beneficial RVSS-derived components in practical products. Simulated models, animal tests and *in vivo* research can provide in-depth information of the correlation between the digestibility/bioaccessibility of the proteins, bioactive peptides, oligosaccharides, polyphenols and other bioactive compounds, and their impacts on human health.

Compared to the purified compound, RVSS extracts with higher ingredient diversity have greater potential in the development of functional foods. With compromised extraction methods, integrative extracts contain considerable amounts of proteins and dietary fibers, meanwhile they can be rich in polyphenols or carotenoids. Interestingly, the biological activities (such as antioxidative capacity) and the physical properties (such as gelling effect) of the extracts can be simultaneously improved by co-extracting (Encalada et al., 2019).

Safety assessment of RVSS-derived edible products is another challenge that needs to be addressed. The presence of undesirable microorganisms can threaten consumers' health. Additionally, the accumulation amounts of fungicides and heavy metals can vary in various parts of the side streams (Šuk et al., 2021). Consequently, case-specific detection is required.

Future study should also focus on sensorial evaluation. The addition dosage of side stream-derived extracts/powders has direct impact upon the consumers' acceptances of the final products (Kultys & Moczkowska-Wyrwisz, 2022; Tiwari et al., 2021; Ziobro et al., 2022). According to the studies reviewed, the sensorial qualities of the products did not change remarkably by adding up to 40% RVSS in the formula (Boruczkowska et al., 2020).

8. Concluding remarks

This review summarized the scattered research on side streams (leaves, peels, pomaces, pulps et al.) of potato, carrot, sugar beet, and beetroot. The potential of these RVSS as sustainable sources for producing high value-added ingredients were thoroughly discussed. Regarding RVSS valorization, current research is focusing mostly on utilization of proteins and fibers. Applying leaf as a potential source of novel foods may be more favorable in comparison to other forms of RVSS, especially in plant-based protein development. The leaves generally contain higher content of total proteins than peels, pomaces, and pulps.

Aside from proteins and dietary fibers, RVSS are also rich in bioactive compounds. Phenolic compounds (i.e., kaempferols, quercetins, caffeic acid, and chlorogenic acid), carotenoids (xanthophyll in carrot leaves), aromatic indoles (betalains in beetroot leaves) have potent activities of scavenging radicals and delaying microbe-induced food spoilage, as well as the capacities of improving eye, gut, and liver health. These bioactive

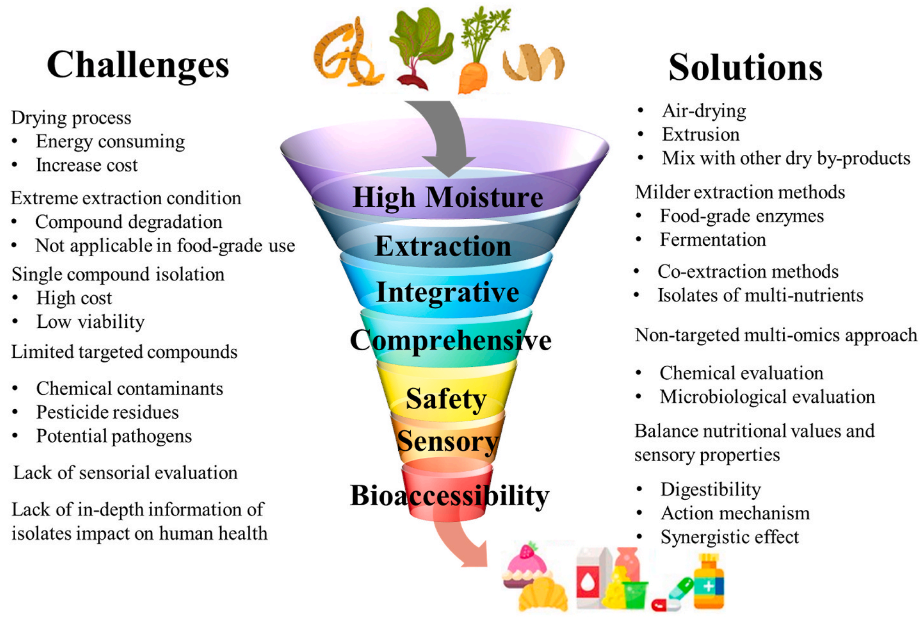

Fig. 2. Challenges and future prospects of valorizing RVSS.

compounds are recommended to be retained in the products as functional ingredients when converted the RVSS to novel food products, in order to maintain their antioxidative, antimicrobial, and other health-beneficial capacities.

Despite the high value of these RVSS being recognized, each source of the side streams has its specific advantages and challenges, both of which should be considered in valorization. Potential safety issue in direct use of leaves as human foods, high consumption of organic solvent during compound extraction from peels, high moisture content retained in pulps, and lack of sensory evaluation on RVSS-modified foods remain as challenges. Moreover, future research needed to create in-depth knowledge on the composition, bioaccessibility, and shelf life of RVSS-derived ingredients and related nutraceutical and pharmaceutical products.

CRediT authorship contribution statement

Y. Zhou – Conceptualization, Visualization, Writing-original Draft, Writing-review & editing, Y. Tian – Writing-review & editing, B. Yang – Conceptualization, Funding acquisition, Supervision, Writing-review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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