TECHNOLOGICAL AND BIOTECHNOLOGICAL PERSPECTIVES ON FOOD WASTE VALORIZATION

Editör: Dr.Öğr.Üyesi Şakir Selçuk SEÇİLMİŞ

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İÇİNDEKİLER

FERMENTATIVE AND MICROBIAL TECHNOLOGIES FOR FOOD REVALORIZATION

Özlem IŞIK DOĞAN[1]

1. INTRODUCTION

Food supply chains span a continuum beginning with primary agricultural production, continuing through processing and retail, and ending with household consumption. In recent years, food processing has emerged as one of the fastest-growing global industries, leading to the generation of large quantities of waste. *Food waste* refers to the discard or failure to use food that is otherwise fit for human consumption. This may occur intentionally or due to neglect, such as improper storage or allowing food to expire (Assis and Gonçalves 2022; Sarker et al. 2024).

In July 2014, the European Commission introduced policy objectives related to the circular economy and waste management. Within this framework, *food waste* was defined as food—including inedible parts—that exits the food supply chain, excluding materials redirected for non-food uses such as bio-based products, animal feed, or food donations (Otles et al. 2015). The COVID-19 pandemic and associated lockdowns revealed critical weaknesses in existing food waste management systems, further elevating food waste and loss as urgent research priorities, especially in industrialized regions (Sarker et al. 2024). In response, international organizations such as UNEP, FAO, and

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IFPRI have revised policies and initiated efforts to reduce food waste, aiming to enhance food security, ensure safety, and combat hunger. These actions support the implementation of *waste-to-wealth* technologies and sustainable waste strategies rooted in the 4R principles: reduction, reuse, recycling, and recovery (Sarker et al. 2024).

Numerous studies have highlighted the severe nutritional and economic impacts of global food waste. It is estimated that about 35% of total food loss occurs across various supply chain stages, from pre-harvest to consumption. Notably, food production, distribution, and retail account for nearly 20% of the 14 million metric tons of waste generated annually (Sarker et al. 2024). A 2011 FAO report estimated that one-third of all food produced for human consumption is lost or wasted. It also distinguished that 54% of losses occur at upstream stages (production and postharvest handling), while 46% occur downstream (processing, distribution, and consumption) (Otles et al. 2015).

The successful realization of a circular economy across industries depends on two key strategies: minimizing waste generation and identifying sustainable solutions for residual waste. Waste valorization—the transformation of waste into value-added products—offers a promising pathway. This concept, central to the emerging biorefinery model, promotes both effective waste management and economic competitiveness by enabling the generation of diverse high-value outputs from waste-derived feedstocks (Garcia-garcia, Stone, and Rahimifard 2019; Nayak and Bhushan 2019).

Food waste is increasingly recognized as a valuable bioresource with the potential to be transformed into a wide array of chemicals, fuels, materials, and other high-value products. Biotechnological processes such as anaerobic digestion, fermentation, and composting allow food and agro-industrial wastes to be converted into biofuels, biomass, biofertilizers, and secondary metabolites (Nayak and Bhushan 2019; Sarker et al. 2024). Moreover, such wastes have been used to produce bio-based adsorbents for removing pollutants from wastewater. Another promising application within the biorefinery model is the recovery of high-value compounds, which can serve as food additives, therapeutics, or bioactive ingredients (Nayak and Bhushan 2019). Additionally, integrating industrial symbiosis strategies into the food manufacturing sector has proven beneficial for enhancing valorization efforts. These initiatives align with circular economy goals and provide significant economic, environmental, and societal advantages. Many countries have adopted policy frameworks to close resource loops by reintegrating food waste into production systems, in line with recent EU policy developments (Garcia-garcia et al. 2019).

Improper disposal of agro-industrial waste can cause serious environmental harm, including aquatic toxicity, soil degradation, groundwater contamination, phytotoxic effects, discoloration of water bodies, and foul odours. Consequently, waste management regulations have become increasingly strict over the past decade. Although waste prevention is the most preferred strategy, the EU’s waste hierarchy emphasizes reuse and recycling for material or energy recovery. Similar principles are supported by the US Environmental Protection Agency (EPA) and the Department of Agriculture (USDA) (Nayak and Bhushan 2019).

In Europe, industrial food waste constitutes a substantial share—between 19% and 39%—of total food waste across the supply chain (Garcia-garcia et al. 2019). Concurrently, the global generation of municipal solid waste (MSW)—estimated at approximately 1.6 billion tonnes per year—has highlighted the urgent need for effective waste management strategies. Asia and

Oceania contribute about 43% of global MSW, while North America and the European Union account for 28%. Notably, in underdeveloped countries, nearly half of the MSW consists of fermentable and biodegradable materials, offering significant potential for biological waste-to-energy conversion (Davila-Vazquez et al. 2008). The agro-food industry generates large volumes of biodegradable solid and liquid waste, primarily consisting of organic residues from processed raw materials. It is estimated that 26% of this waste stems from the beverage sector, followed by dairy (21%), fruits and vegetables (14.8%), cereals (12.9%), meat (8%), oils (3.9%), and fish processing (0.4%), with other industries accounting for the remaining 12.7%. These waste streams typically exhibit high moisture content, elevated organic load, and biological instability, which facilitate microbial growth and pose significant challenges for storage, treatment, and disposal (Nayak and Bhushan 2019).

Reducing or eliminating food waste has become a central focus for both policymakers and the food industry. In the context of a circular economy, food waste valorization aims to convert waste into useful products such as fuels, materials, and chemicals. Beyond generating organic fertilizers, animal feed, biofuels, and electricity, such practices provide substantial economic, social, and environmental benefits. Over the last decade, research has increasingly focused on the transformation of food waste into edible ingredients, functional foods, nutraceuticals, pharmaceuticals, and cosmetics. However, ensuring industrial applicability requires consideration of several factors: the adaptability of processes to different waste types, integration within biorefinery operations, and long-term environmental and economic sustainability. Accordingly, the selection of suitable extraction methods for bioactive compounds must balance multiple criteria to ensure process efficiency and value recovery.

2. BIO-HYDROGEN PRODUCTION FROM FOOD WASTE: DARK FERMENTATION

The global reliance on fossil fuels for energy—currently accounting for approximately 86% of total consumption—has raised critical concerns regarding environmental sustainability and climate change (Dong et al. 2009). Hydrogen (H_2), the most abundant element in the universe, is increasingly recognized as a viable long-term energy carrier due to its high energy density—2.75 times greater than hydrocarbon fuels—and clean combustion, which produces only water (Kim, Kim, and Shin 2009; Wu et al. 2005). Additionally, it can be efficiently converted into electricity via fuel cells. However, because H_2 does not exist in elemental form on Earth, it must be produced through various methods. Currently, more than 90% of global hydrogen production is derived from fossil fuels through steam methane reforming and coal gasification—methods that are cost-effective but environmentally detrimental due to their high greenhouse gas emissions (Kim et al. 2009; Wu et al. 2005; Yun et al. 2018).

Given these limitations, the development of renewable, low-emission hydrogen production technologies have become a key research priority. Biological hydrogen production (BHP) offers a promising alternative, utilizing the metabolic pathways of specific microorganisms to produce H_2 as a by-product (Yun et al. 2018). BHP includes several pathways such as direct bio-photolysis, indirect bio-photolysis, photo-fermentation, and dark fermentation (Im et al. 2012; Lalman et al. 2013; Wu et al. 2005; Yun et al. 2018). Among these, dark fermentation stands out for its practical advantages, including light-independent operation, rapid hydrogen production, low operating costs, and the ability to process a wide range of organic substrates.

In dark fermentative hydrogen (H_2) production, inocula are typically derived from anaerobic environments such as digester sludge, sewage sludge, compost, manure, and soil, providing both environmental and economic benefits (Im et al. 2012; Lalman et al. 2013). By integrating dark fermentation into waste management systems, it is possible to simultaneously reduce the environmental burden of organic waste disposal and generate clean, renewable energy (Im et al. 2012). This dual advantage positions dark fermentation as a compelling component of future sustainable energy strategies. Owing to its elevated volatile solids (85–95%) and moisture content (75–85%), FW is prone to generating leachate and malodours if not appropriately managed during collection and transportation. Nonetheless, its substantial energy potential renders it an attractive substrate for the production of biofuels and value-added chemicals, thereby offering a dual benefit of waste mitigation and resource recovery. In particular, the recovery of hydrogen (H_2) during treatment processes presents an opportunity for generating a clean energy carrier and a versatile chemical feedstock (Yun et al. 2018).

Early studies on dark fermentative hydrogen production primarily utilized pure cultures such as *Clostridium butyricum* and *Enterobacter aerogenes* with sterile substrates like glucose or starch (Jo et al. 2007). However, pure culture systems are prone to contamination, and the low hydrogen yields from costly substrates have limited their economic viability as alternatives to chemical or electrochemical methods (Nath and Das 2004). Moreover, mixed microbial cultures are favoured over pure cultures due to their operational simplicity and adaptability to diverse waste substrates. Pure cultures are difficult to maintain under real conditions because native microorganisms are constantly introduced into the system. While mixed cultures include both H_2 producers and non-producers, shifts in microbial community composition have been shown to significantly influence H_2 production efficiency (Im et al. 2012). Regarding bacterial community, Im (Im et al. 2012) determined that the microbial community dominated by Proteobacteria (50%) and Bacteroidetes (25%) at the beginning of dark fermentation hydrogen (H_2) bioreactor fed with equal volumes of food waste and sewage sludge; but after 6 hours, Firmicutes became dominant (>97%). Within 48 hours, Clostridium species such as *C. sordellii*, *C. perfringens*, and *C. butyricum* prevailed, correlating with the accumulation of butyric acid.

In terms of fermentation substrate, , the use of carbohydrate-rich organic wastes—such as agricultural residues and food industry effluents—has emerged as a more sustainable and cost-effective approach, offering simultaneous waste treatment and renewable energy generation (Kapdan and Kargi 2006). (Davila-Vazquez et al. 2008) reviewed fermentative hydrogen production using various substrates—including pure carbohydrates (e.g., glucose, xylose, sucrose, lactose), molasses, starch, fruit waste, palm oil mill effluent, food waste, and other organic solid wastes—focusing on substrate feasibility and key process parameters. While most studies utilized pure cultures such as *Clostridium* spp., these strict anaerobes require oxygen-free environments and costly reducing agents (e.g., L-cysteine), limiting their practical application. As a cost-effective alternative, mixed cultures—including facultative anaerobes like *Enterobacter* spp.—have been employed. Yokoi et al. (Yokoi et al. 1998), for instance, successfully produced hydrogen using a combination of *Enterobacter* and *Clostridium* spp. without the need for reducing agents. To enhance hydrogen yields, various pretreatments of sludge-based mixed inocula (e.g., heat shock, acidification, methanogen inhibition, freezing/thawing, sterilization, and sonication) have been studied to favor spore-forming hydrogen producers over non-spore-forming methanogens. Since *Clostridium* spp. can form endospores under stress, selective enrichment of these bacteria may significantly improve hydrogen production from organic waste.

Most hydrogen production from such wastes has been conducted in batch systems, whereas continuous operations have shown frequent instability—even under defined conditions—and the causes, particularly in relation to microbial community dynamics, remain unclear (Jo et al. 2007). Continuous anaerobic hydrogen production systems often suffer from operational instability over time, prompting investigations into the underlying causes. Interestingly, the total hydrogen production time in batch processes—accounting for the lag phase—was found to be comparable to the hydraulic retention time used in continuous systems for organic solid waste treatment (Kim et al. 2009; Wu et al. 2005). However, continuous systems often suffer from the presence of indigenous non-H_2-producing bacteria that hinder process stability (Jo et al. 2007; Kim, Han, and Shin 2008). In several studies, batch processes have demonstrated higher hydrogen yields than continuous operations; for example, olive pulp waste treatment in batch mode produced five times more H_2 than in continuous mode (Gavala et al. 2006). Despite this, batch systems present a key operational challenge: the repeated need for inoculum preparation, which is labor-intensive and may introduce contamination.

Regarding batch fermentation operations, While H_2 yields are often expressed on a hexose basis, this metric alone is insufficient to assess feedstock suitability. More accurate assessments are achieved using yields based on volatile solids (VS) and chemical oxygen demand (COD), as these relate more directly to the energy content and biodegradability of organic wastes. Although FW, sewage sludge, and livestock waste may show similar H_2 yields on a hexose basis, FW's significantly higher carbohydrate content (30–70% vs. <10%) makes it a more promising candidate. Various pretreatment method can be implemented -including thermal, alkaline, and acidic treatments- were applied to increase process yields up to 20-fold compared to untreated FW (Im et al. 2012; Jang et al. 2015; Kim et al. 2009; Lalman et al. 2013). For instance, pre-treatment selectively suppresses non-H_2-producing microorganisms like lactic acid bacteria (LAB), which dominate untreated FW and are metabolically unrelated to H_2 production. LAB also produce bacteriocins that inhibit hydrogen-producing bacteria. In contrast, pre-treated FW shows enrichment of H_2-producing microbes (Yun et al. 2018).

In continuous organic waste treatment systems, the primary objective is to maintain a highly active microbial community to ensure stable and efficient hydrogen (H_2) production. Accordingly, the volumetric hydrogen production rate (VHPR) is considered a more relevant performance indicator than H_2 yield (Yun et al. 2018). Despite efforts, the highest reported VHPR from food waste (FW) remains at 10.7 L H_2/L/day, considerably lower than the 15 L H_2/L/hour achieved with liquid substrates like sucrose wastewater, largely due to the slower hydrolysis of solid waste (Wu et al. 2005; Yun et al. 2018). Continuous stirred tank reactors (CSTRs) are the most commonly used systems for continuous H_2 production from FW, although other configurations—such as anaerobic baffled reactors, membrane bioreactors, and sequencing batch reactors—have been employed to decouple solid retention time (SRT) from HRT (Yun et al. 2018). Different studies on CSTRs indicate contrasting outcomes which presents there is no universally optimal condition; instead, the effectiveness of operational parameters is highly dependent on variables such as feedstock composition, inoculum source, and other conditions including temperature and pH. Notably, continuous systems more commonly operate under thermophilic conditions than mesophilic, in contrast to batch studies (Yun et al. 2018).

A key constraint in hydrogen production by fermentative bacteria is the limited electron-based yield that can be achieved. Due to inherent biochemical and thermodynamic restrictions, the theoretical maximum hydrogen yield is four moles per mole of glucose, which is only possible when glucose is fully oxidized to form two moles of acetate. This reaction also produces carbon dioxide, protons, and hydrogen, and is associated with a Gibbs free energy change ($\Delta G°'$) of –145 kJ/mol (Nugroho, Kleerebezem, and Bachmann 2021). In mixed culture fermentative systems, actual hydrogen yields are typically below 2 mol H_2/mol glucose—well below the theoretical maximum—due to biochemical constraints involving electron carriers. Hydrogen generation is limited to metabolic steps linked to formate production or ferredoxin reduction, and cannot occur via NADH-dependent pathways due to thermodynamic barriers. Since fermentative hydrogen production only partially oxidizes the substrate, it is often coupled with secondary processes, such as anaerobic digestion to produce methane or phototrophic conversion to generate additional hydrogen and carbon dioxide (Nugroho et al. 2021).

Food waste, when left untreated, naturally decomposes due to diverse indigenous microorganisms such as lactic acid bacteria (LAB), propionic acid bacteria (PAB), fungi, and coliforms (Yun et al. 2018). These non-H_2 producers can outcompete hydrogen-producing strains if not properly controlled. To address this, alkali pretreatment (pH 12.5–13.0) has been applied to eliminate non-H_2-producing microbes while preserving spore-forming bacteria like *Clostridium* spp. and *Bacillus* spp. that survive and regenerate under suitable conditions (Lalman et al. 2013). Notably, *Clostridium* spp.—the primary H_2-producing genus—are naturally present in various food sources and have been extensively studied in food and medical microbiology. This supports the hypothesis that food waste may serve both as a substrate and a natural inoculum source for hydrogen production if appropriately pretreated (Yun et al. 2018).

Molecular fingerprinting techniques (DGGE and T-RFLP) revealed that microbial community shifts—from *Clostridium* spp. to *Lactobacillus* spp.—led to a metabolic transition from hydrogen to lactic acid fermentation (Jo et al. 2007). Although *Clostridium* spp. can theoretically produce up to 4 mol H_2/mol glucose via acetate production, actual yields are often less than 50% due to thermodynamic limitations, competition from non-H_2-producing bacteria (non-HPBs), and H_2-consuming acetogenic pathways. Butyrate, a more thermodynamically favorable product, yields only 2 mol H_2/mol glucose and is more commonly produced due to enzymatic and redox constraints. Additional yield losses arise from the presence of non-HPBs like *Bacillus* spp. and LAB, which survive pretreatment and inhibit H_2 production. Acetogenic bacteria such as *C. aceticum* and *C. scatologens* also reduce H_2 availability by converting it into acetate, especially at high substrate concentrations. Because these acetogenic H_2-consuming reactions significantly impact yields, the present study employs flux balance analysis (FBA) to quantify their contribution. FBA offers a systems-level approach to modeling metabolic networks, enabling the identification of limiting pathways and informing strategies to enhance biohydrogen production efficiency (Lalman et al. 2013).

2.1. Limitations of Dark Fermentation

2.1.1. Low H_2 Yield

A key limitation in achieving high hydrogen yields from food waste via dark fermentation is the persistent presence of indigenous non-H_2-producing microorganisms, particularly lactic acid bacteria (LAB). In the absence of pretreatment or inoculum, FW fermented at mesophilic conditions (e.g., 35°C) tends to be degraded primarily into lactate rather than hydrogen (Kim et al. 2009). Moreover, microbial dominance of LAB has been linked to unstable H_2 production in continuous systems as well (Jo et al. 2007). LAB not only lack metabolic pathways relevant to H_2 generation but also suppress hydrogen-producing bacteria through the production of inhibitory compounds such as bacteriocins. Consequently, various pretreatment strategies—including thermal, alkaline, and acid shocks—have been employed to selectively inhibit LAB while enriching spore-forming hydrogen producers like *Clostridium* spp. (Kim et al. 2009). In addition, FW's composition itself poses inherent challenges; although it contains high levels of carbohydrates favorable for H_2 production, it also includes proteins and lipids, which contribute minimally. Experimental data show that carbohydrate-rich substrates such as cabbage, rice, and carrots can yield 19.3–96.0 mL H_2/g VS, while protein- and lipid-rich wastes produce negligible H_2 (Lalman et al. 2013). Moreover, glycerol—derived from lipids—is unsuitable for H_2 production but better suited for solvent generation Although proteins can yield limited hydrogen via amino acid degradation, much of it is consumed through competing pathways such as the Stickland reaction (Lalman et al. 2013).

2.1.2. Economic Feasibility

Although the production of hydrogen (H_2) from food waste (FW) via dark fermentation offers a renewable and environmentally friendly pathway, its economic feasibility remains uncertain. Based on a high-yield scenario (2.26 mol H_2/mol hexose) at an organic loading rate (OLR) of 100 kg COD/m^3/day, a techno-economic assessment was performed assuming a fermenter capacity of 200 m^3 operating 360 days per year over a 20-year lifespan. The total capital and annual operating costs were estimated at 1,636,560 USD and 548,568

USD/year, respectively. With a projected profit of 360,000 USD/year from FW treatment and an annual H_2 output of 949,200 m^3, the production cost was calculated as 3.2 USD/kg H_2. Although this is below previously reported costs (10–30 USD/kg H_2), it remains higher than the current market selling price of H_2 (0.5–3.2 USD/kg), suggesting that dark fermentation alone may not yet be commercially viable (Yun et al. 2018).

In conclusion, while dark fermentation remains a promising route for biohydrogen production from food waste, its stand-alone economic and technical limitations necessitate process intensification. Further efforts are required to scale up these systems and address process stability—particularly regarding methane suppression—to make biohydrogen production from food waste both sustainable and commercially viable (Yun et al. 2018).

2.2. Green Extraction Procedures

Fermentation is a cost-effective, low-energy method for food preservation that enhances nutritional value by generating bioactive compounds, while also improving flavor, texture, digestibility, and nutrient absorption (Knez, Kadac-Czapska, and Grembecka 2023). There are three types of fermentation which are spontaneous, backward, and controlled types. In spontaneous fermentation, the process occurs spontaneously, driven by the sequential and competitive interactions among diverse microbial populations, whereby the most ecologically adapted strains prevail and establish dominance within the microbial community of the fermenting substrate. In a backward type fermentation, a portion of a successfully fermented previous batch is used as an inoculum to initiate a new fermentation. In contrast, controlled fermentation involves the use of well-defined, previously isolated microbial strains, typically comprising various species of lactic acid bacteria, yeasts, and fungi (Knez et al. 2023).

Another method for food waste valorisation is green extraction approaches which enables resource recovery and utilization of essential elements in terms of sustainable waste management. For instance, Sridhar et al. (Sridhar, Akram, and Banat 2024) evaluated date seed, a by-product of date processing, valorisation approaches. According to this study, microbial fermentation-based extraction techniques offer a sustainable and efficient substitute for conventional chemical extraction methods. Oehlenschläger et al. (Oehlenschläger et al. 2024) defines microbial fermentation based methods as utilisation of microbial activity to break down complex matrices which enables the release of bioactive compounds through their metabolic pathways. Several studies indicated that microbial extraction approaches showed greater extraction efficiency than traditional solvent-based methods, minimizing the need for harsh chemical agents (Ameur et al. 2022; Knez et al. 2023; Kuhad et al. 2023; Sridhar et al. 2024). Knez et al. (Knez et al. 2023) determined that fermentation using specific microbial strains like *Aspergillus awamori* can significantly reduce phytate levels—from 0.4 to 0.11 mg per 100 g—enhancing the bioavailability of key minerals. On the other hand, yield and quality of bioactive compounds can be enhanced by optimization of fermentation parameters such as, enzyme selectivity, ambient temperature, acidity levels, and the amount of available substrate.

2.3. Fungal Treatment of Food Waste

Fungal-based biological applications have an emerging role in the biological pre-treatment of organic waste due to their multifunctional capacity and proficiency in synthesizing a range of enzymes (Chaurasia et al. 2022). Bio-waste, solid waste or organic waste materials contains macromolecules such as lignin, lignocellulose, hemicellulose, fats, proteins, and vitamins. Decomposition of these constituents may produce harmful gases and components while their proper management can also generate a variety of valuable products, including biogas, sugars, electricity (through biogas or alternative fuels obtained from biowaste valorization), short-chain carboxylic acids, fertilizers, and several other beneficial compounds (Chaurasia, Bharati, and Singh 2025).

Among aforementioned macromolecules, lignocellulosic biomass, primarily derived from agricultural and forestry residues, is abundant and characterized by a high carbohydrate content (55–75% on a dry weight basis), making it a promising and readily accessible feedstock for ethanol production. In order to reach maximum carbohydrates utilization from the biomass, a pre-treatment step is required to address the inherent recalcitrance of biomass and thereby enhance its susceptibility to hydrolytic enzyme action (Wan and Li 2012). In fungal pre-treatment method, the process is run in the temperature range of 25-30^{o}C, with using minimum water, at atmospheric pressure and without the use of any chemicals (Chaurasia et al. 2025). Several studies examined the effect of fungal pre-treatment on different biomass feed stocks, including corn stover, wheat straw, rice straw, cotton stalks, and woody biomass (Bak et al. 2009; Dias et al. 2010; Keller, Hamilton, and Nguyen 2003; Shi et al. 2009; Xu et al. 2010; Yu et al. 2009).

For instance, spent coffee grounds (SCGs), a type of bio-waste generated in significant quantities following coffee brewing, are estimated to amount to approximately 6 million tons annually on a wet basis, although the precise global volume remains uncertain (Johnson, Liu, and Lu 2022; Mussatto, Machado, and Martins 2011). Spent coffee grounds represent a promising feedstock for bio-based and chemical processes aimed at producing high-value products for the cosmetics, pharmaceutical, and food industries, regarding that they are rich source of polysaccharides, proteins and lipids (Chaurasia et al. 2025). Pereira et al. (Pereira et al. 2022) studied the biological pretreatment of coffee waste by acidogenic fermentation using two fungi, i.e. *Paecilomyces variotii* NRRL-115 and *Trametes versicolor* CBS 109428, which showed a marked increase compared to control sample, in addition to generation of acetic acids, propionic acids and butyric acids.

Regarding lignin-degrading microorganisms, white-, brown- and soft-rot fungi, and some ruminant bacteria can metabolise lignocellulosic biomass while white rot fungi are considered the most efficient organisms for delignification owing to their distinct and highly effective lignin-degrading enzyme systems (Wan and Li 2012). In terms of bacterial pre-treatment of organic solid waste, *Bacillus licheniformis* and *Bacillus oryzaecorticis* have demonstrated significant potential in facilitating the degradation of food waste (Chaurasia et al. 2022). Mu et al. (Mu et al. 2023) found that *Bacillus oryzaecorticis* degraded starch and a substantial release of reducing sugars was observed, contributing hydroxyl and carboxyl (COOH) groups to the structure of fulvic acid molecules *Bacillus licheniformis* exhibited a beneficial impact on the structural composition of humic acid.

2.3.1. Citrus Processing Waste

The citrus processing industry holds a key position within the agro-industrial sector, with oranges being the most extensively cultivated fruit globally—representing approximately 50–60% of total citrus production—while other species such as lemons, limes, mandarins, and grapefruits also contribute significantly to industrial applications (Demetrio A. Zema et al. 2018). Following processing, the citrus sector generates waste water and solid/semisolid residues. Citrus processing waste (CPW) accounts for approximately 50% to 70% by weight of the processed fruit, with variations depending on the processing technology and fruit cultivar, and its global annual production is estimated to approach 10 million tons. The disposal of CPW incurs substantial costs, and improper or unauthorized disposal may lead to potential soil contamination and in certain cases, it may also result in the degradation or destruction of aquatic ecosystems, due to its low pH and high organic compounds content (Mahato et al. 2021; D A Zema et al. 2018; Demetrio A. Zema et al. 2018). It is accepted that the conventional methods of CPW treatment are currently inadequate and pose challenges regarding environmental sustainability and energy efficiency (Wei et al. 2017). However, latest studies suggest conversion applications in bio-refineries have been the most profitable and environmental approaches which enables the production of several products.

A biorefinery can be defined as a facility that combines biomass conversion processes and technologies to generate fuels, energy, and chemicals from waste biomass (Martín et al. 2010). Several authors proposed different biorefinery strategies generating several end-products. For instance, Pourbafrani et al. (Pourbafrani et al. 2010) proposed a new approach to produce ethanol, biogas and limonene from CPWs via *Saccromyces cerevisiae* fermentation in a biorefinery. Siles Lopez et al. (Ángel Siles López, Li, and Thompson 2010) also investigated ethanol production stated that *Saccharomyces cerevisiae* fermentation is more effective for the bioconversion of orange peel into ethanol than ethanologenic yeast *Kluyveromyces marxianus*.

Biogas, primarily composed of methane (50–70%) and carbon dioxide (30–50%), is the main product of anaerobic digestion of organic substrates, with agro-industrial waste serving as an effective feedstock due to its content of mineral ions that can enhance methane yield (Bozym et al. 2015; D A Zema et al. 2018). The methane yield from CPW is influenced by several factors, including pH, temperature, and the availability of nutrients for microorganisms, with the citrus cultivar playing a secondary role; however, similar to alcoholic fermentation, the anaerobic digestion of CPW is primarily hindered by the presence of essential oils in the substrate (Mahato et al. 2021; D A Zema et al. 2018). Several studies indicated (Wei et al. 2017; D A Zema et al. 2018; Demetrio A. Zema et al. 2018) that although thermophilic conditions enable an increase methane generation and accelerated degradation of matter, mesophilic processes lead to enhanced process stability. On the other hand, several applications including solid state fermentation, biological removal, aeration, distillation, solvent extraction and steam explosion were explored as strategies to lower the concentration of essential oils in the substrate before undergoing anaerobic digestion (Mamma, Kourtoglou, and Christakopoulos 2008; Ruiz and Flotats 2016).

(Koppar and Pullammanappallil 2013), determined that in a citrus processing facility processing 600 tons of fruit per day, the biogas generated from waste streams is sufficient to cover the plant's electricity and fuel needs, with any surplus electricity potentially available for sale. Although, biomethane production from CPW presents a promising option and is currently achievable through co-digestion with complementary substrates, there are challenges associated with the seasonal availability of CPW and the toxic effects of essential oils on microorganisms which have not been overcame yet (D A Zema et al. 2018).

Moreover, (Koppar and Pullammanappallil 2013) reported methane generation from orange peel can be enhanced through the pretreatment of orange peel using selected strains of *Sporotrichum*, *Aspergillus*, *Fusarium*, and *Penicillium*, due to improvement of nutrient availability in the medium and decline in the levels of antimicrobial compounds as a result of the yeast activity (Ángel Siles López et al. 2010). However, the removal and/or recovery of limonene is regarded as a critical step prior to biomass fermentation for biogas or biofuel production (Mahato et al. 2021). Because, limonene (91–95%) is the predominant component in citrus essential oils, followed by pinolene (1.83–2.61%), n-octanol (1.50–1.64%), myrcene (1.3%), α-pinene (0.28–0.5%), linalool (0.39%), β-pinene (0.38–1.05%), γ-terpinene (0.41–1.09%), camphene (0.27–0.35%), and decanal (0.11–0.35%), which have antimicrobial effect during fermentation step. There are several methods for removal and/or recovery of limonene, including aeration, biological treatment, filtration, steam distillation and son on. Among them, biological treatment is mainly driven by fungal activity, particularly through the use of selected strains such as *Sporotrichum*, *Aspergillus*, *Fusarium*, and *Penicillium*, or by employing enzymes derived from fungal sources like *Aspergillus* and *Penicillium* (Mahato et al. 2021).

In addition, (Garzón and Hours 1992) found that a strain of *Aspergillus foetidus* can be used for pectic enzyme manufacture in solid-state cultures. Another study revealed manufacture of multienzyme preparations including pectinolytic, cellulolytic, and xylanolytic enzymes via the mesophilic fungi *Aspergillus niger* BTL, *Fusarium oxysporum* F3, *Neurospora crassa* DSM 1129 and *Penicillium decumbens*, under solid-state fermentation of dry orange peel is applicable (Mamma et al. 2008). Orange peel waste has also been utilized for single cell protein production which is widely used as alternatives for protein-reach foods. Previous studies indicated that productions derived from solid-state fermentation of acid-pretreated orange peel by *Geotrichum candidum* cultures contains 35–40% crude protein with exceptionally high in vitro digestibility (Mahato et al. 2021).

3. CONCLUSION

Given the alarming projections that municipal solid waste will rise from 2.1 billion tons in 2023 to 3.8 billion tons by 2050, and that food waste constitutes a substantial proportion—ranging from 15% to 63%—of these waste streams, it is evident that sustainable strategies for food waste management are urgently needed (Chaurasia et al. 2025; Jang et al. 2015). With approximately 13% of global food production lost between harvest and retail, and an additional 19% wasted at the consumer and service levels, the environmental and public health implications are profound (Chaurasia et al. 2025; Nations 2024). Microbial valorization offers a promising, eco-friendly, and cost-effective approach to convert food waste into valuable products such as biofuels, organic acids, enzymes, and functional ingredients. Harnessing the metabolic versatility of microorganisms not only mitigates the environmental burden of food waste but also aligns with circular economy principles by transforming waste into resources. Therefore, microbial pathways represent a critical component in the global effort to manage food waste more effectively and sustainably.

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STARCH IN WASTE RECYCLING AND RECOVERY

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1. INTRODUCTION

Starch, which is the primary component of cereals, is a significant processed output of both the agricultural and food sectors. Starch is commonly utilized as an intermediate product to be converted into other products, but it can also be a end product derived from grain. Starch's wide use in food and other sectors makes it one of the most common sectors worldwide. Obtaining starch, then modifying the starch, or using the starch as a raw material and processing it into food products consist of various stages, and each of these processes constitutes a step that can be evaluated as regards food waste. Starch is produced from basic grains, and the production and processing stages of these grains create waste. In addition, when processing food and agricultural products containing starch, wastewater with high starch content is produced. The release of these wastes into nature can cause serious environmental and economic problems, and the recovery of starch from wastewater constitutes an important recovery within the aim of the evaluation of these wastes. The starches produced can be utilized in the manufacture of lactic acid and ethanol, both in cuisine and a diversity of other industries. In addition, it enables energy production with a more environmentally friendly approach by being used in the production of biogas, that is a new and

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environmental friendly energy production method. The waste parts of starch production and starch-containing product processes have a serious recovery potential in these ways. Another option for the extirpate of waste in the starch sector is the use of alternative agricultural products, which creates a new field of study as it reduces the amount of waste while providing starch.

2. FOOD WASTE MANAGEMENT REQUIREMENT

Food waste is now an unavoidable problem, with both household consumption and commercial food services causing huge amounts of food waste globally. Countries around the world have reached a consensus to save food and reduce waste, considering the increasing population and urgent needs, while highlighting the risks to human society, such as climate change, the continuity of human livelihoods and agriculture. The United Nations General Assembly declared September 29 the International Day of Awareness of Food Loss and Waste to raise awareness of global food issues (Li et al., 2025). The Food and Agriculture Organization of the United Nations' Sustainable Development Goal addresses food loss and food waste and aims to reduce global food waste per capita by 50% at the consumer and market levels, and to decrease post-harvest loss and losses in supply chains and production levels. One of the key areas for accomplishing this objective is the function of economic development organizations and the sustainable management of food waste (Makroo et al., 2021). The disposal of huge quantities of food waste is a barrier to the modern society's sustainable development. In this case, rational processing and maximum use of food waste is a fundamental approach to building a resource-saving society. (Li et al., 2025).

With the implementation of more restrictive environmental regulations and the increasing costs of storage and waste handling, it is becoming more considerable for the food industry to obtain higher value and maximum efficiency from the production phase. There has been increased interest in recycling and reusing by-products from industrially produced waste (Devereux et al., 2011).

3. STARCH

Starch, which is obtained primarily from grains, legumes, and tubers, is the most significant carbohydrate in the human nutrition and one of the most widespread glucose polymers in food. It can be obtained from several areas of a plant, such as fruits, leaves, seeds, and roots. Morphologically, starch granules can be of various shapes according as the source of the starch, consisting of spherical, polygonal, segmented or lenticular shapes (Makroo et al., 2021).

Starch is chemically a polymer made up of glucose units connected connected each other with glycosidic bonds. Starch is a D-glucan polymer composed of two polysaccharide components, amylose and amylopectin. Both components consist solely of glucose, and the amylose portion exists mainly in the form of a linear α-(1,4)-glycosidic bond, while the amylopectin portion exists predominantly in the form of a branched α-(1,6)-glycosidic bond. The amylose:amylopectin ratio varies from one starch to another (Devereux et al., 2011). The chemical and physical properties of amylose and amylopectin differ significantly due to their linear and highly branched structures, respectively. Amylose is insoluble in water and contributes to increasing the gelatinization capacity of starch, while amylopectin is easily soluble in water and is utilized for increase adhesive properties. The functionality of starch depends mainly on the amylopectin and amylose fractions. In addition, the morphology and surface properties of starch granules, together with the amount of lipid, protein and phosphorus content, affect starch behavior in terms of adhesive properties and water binding capacity (Makroo et al., 2021).

Starch is utilized in the food sector as a gelling, thickening, and/or stabilizing agent, as well as an emulsifier, sweetener, and binder. Starch is a versatile raw material owing to its wide use in the paper, chemical, textile, pharmaceutical, and biotechnological industries (coatings/films, adhesives, oil drilling additives, drug carriers, biofuels, etc.) as well as its significance in the food industry. The type of starch selected for specific industrial purposes is chosen based on its availability and its physicochemical properties, which vary depending on the source from which the starch is obtained. Starch has been derived from a diversity of plant sources, including wheat, rice, potatoes, and corn for centuries due to its easy availability in nature, biodegradability, renewable character and endless modification possibilities due to its abundant -OH chemistry (Makroo et al., 2021).

4. RECYCLING OF STARCH WASTES

Three primary factors have motivated the quest for alternative starch sources: the growing market demand; the industry's need for novel starches with distinct physicochemical, structural, and functional characteristics from traditional starch sources; and the need to feed the widening global population. In relation to food waste, the world population is estimated to rising up over 9.7 billion by 2050. Therefore, supplying sufficient food to the rapidly growing population poses a worldwide challenge (Kringel et al., 2020).

4.1. Usability Of Starch-Containing Water As Potato Industry Waste

In the processing of potato starch, a large amount of waste residue containing various organic substances such as protein, carbohydrate, starch, etc. is formed, and if this waste material is piled outside without going through any disposal method, it leads to waste of raw materials and negative consequences for the environment. This recycling industry, however, is confronted with significant obstacles. Naturally, if these waste materials are not disposed of correctly, the economic and environmental drawbacks may outweigh the benefits of starch processing. First of all, fresh waste residue contains a considerable amount of water, about 80%, is not suitable for storage and long-term transportation, so it is usually stacked outside without any waste, for a large variety of bacteria inside, the degradation of organic matter, with a terrible smell, the environment can be destroyed. Alternatively, if this potato waste material is dried and converted into dry feed, the cost is out of control, even if it is used directly as feed or buried locally, it may lead to soil and groundwater pollution, meanwhile, a significant waste is generated due to the low utilization rate. As a result, the waste residue treatment sector must stay up with the widely potato starch production industry (Wu, 2016).

Potato processing involves several mechanical steps that constantly require water, such as washing, peeling, cutting or slicing. Therefore, the resulting wastewater contains high concentrations of starch as free suspended solids. Starch makes up about 65-80% of the dry weight of potato tubers. The granular and molecular structure of potato starch-characterized by lengthy amylopectin chains, large, smooth granules, and high-molecular-weight amylose-gives it some unique characteristics. Numerous approaches are accessible for material separation from wastewater; hydrocyclones and centrifuges are typical tools for starch-water separation, and sometimes, technologies that are related with membranes such as Reverse Osmosis and the increasingly popular Membrane Bioreactors are utilized (Devereux et al., 2011).

4.2. Conversion Of Starch Wastes Into Lactic Acid And Ethanol

Microbial mixed cultures can produce ethanol anaerobically from glucose, while lactic acid can be produced from starch conversion. This was observed in both batch trials and continuous chemostat studies of anaerobic digester sludge, demonstrating that the production of lactic acid from starch and the fermentation of ethanol from glucose solutions are both reproducible processes. Anaerobic conversion of carbohydrates is used in many different industries, including food preservation, alcohol and biochemical production, as well as the conversion of food waste into bioproducts and bioenergy. Anaerobic fermentation with an added acid stage can produce general fermentation products such as hydrogen gas organic acids and alcohols. Examples of the usefulness of fermentation end products obtained in waste utilization include the use of food waste lactic acid as a precursor for producing bioplastics or hydrogen and ethanol as possible fuels. Because both lactic acid and ethanol are useful byproducts of carbohydrate fermentation, investigating the conditions that support their production is of potential industrial importance. (Darwin et al., 2018).

4.3. Conversion Of Food Waste Into Biogas And Biofuels

Global fuel demand continues to increase day by day. A major issue is the large-scale depletion of fossil fuels and their effects of environmental through pollution. At the same time, the disposal of food waste is a difficult issue in solid waste management because of the fact that one-third of all food consumed is disposed of as waste. (Onyeaka et al., 2022). Standard waste management methods, including incineration of food waste and landfills, are considered hazardous to the environment. Starch makes up the majority of food waste materials, which also contains a variety of biomolecules, such as cellulose, lipids, proteins, sugars, vitamins, and more. These polysaccharides can be broken down into monosaccharides like glucose through hydrolysis. Sugars obtained from enzymatic hydrolysis of food waste can be fermented by microorganisms to produce ethanol. Starch is plentiful in the human food system and might be used to produce bioethanol. Ethanol is used as a fuel because of its numerous benefits, which include a low cost, a lower thermal energy content (around 45% less per gallon than diesel), and fewer contaminants than gasoline or diesel (Onyeaka et al., 2022).

There are two well-established technological pathways for producing biogas from agricultural waste: anaerobic biodigestion and gasification, the latter involves thermochemically converting biomass, which contains carbon in its composition, into a gaseous fuel output. Gasification technology is usually considered for solid biomass wastes with minimum moisture and maximum calorific value (e.g. lignocellulosic materials). Biodigestion is a more appropriate resolution for the energetic conversion of an aqueous organic wastewater such as cassava pulp waste.(Sanches et al., 2017).

A waste biorefinery based on biological digestion of wastewater aims to overcome a double goal: first, the alleviation of an environmental problem, as anaerobic digestion neutralizes the pollutant potential of the wastewater; second, significant resources can be recovered. (Sanches et al., 2017).

Commercial cassava starch extraction involves grating cassava roots, then separating the fibers, then dewatering the starch and drying the product. The procedure uses a lot of water, (~18 m^3), thermal and electrical energy (~445-695 kWh, and ~90-260 kWh respectively) per ton of starch produced (Padi and Chimphango, 2020). As a result, large volume wastewater containing ~0.157 kg starch/m^3 is produced at a rate of 12-20 m^3/ton starch. Similarly, the separated fiber called cassava bagasse is superior in starch (~75% w/w). Consequently, in order for the starch plant to meet discharge standards, costly treatment procedures are necessary. When combined with high water and energy consumption in starch processes and high waste treatment costs, it becomes necessary to integrate waste treatment with resource recovery. There are many possible transformation routes for cassava waste, including thermochemical and biological processes. Anaerobic digestion is an appropriate energy recovery method for agroindustrial wastes with high moisture content, in contrast to thermochemical processes like combustion and gasification (Padi and Chimphango, 2020).

Anaerobic fermentation is a typical bioconversion method for converting food waste into biogas and biofertilizer, offering a scaled-up and value-added approach to solving the food waste disposal problem. Food waste is a source of chemicals from a chemical perspective because of its varied composition, including protein, carbohydrates, fats, etc. Especially starch-rich food waste, such as rice, potatoes, etc., constitutes a significant proportion of food waste and is rich in carbohydrates, namely starch, dietary fiber, which are an ideal source of chemicals and fuelsThis is spurring tremendous efforts to develop new technologies for transforming food waste into new products. Recent developments have opened up a new avenue for the effective use of food waste, showing that there is a great possibility of using food waste for the generation of high-value chemicals such as sugars, biofuels, etc. By gaining an understanding of the molecular structure, starch food is a C6 polymer with glucose units connected each other with α-1, 4-glucosidic bonds, that can be hydrolyzed to glucose monomers by acid catalysis. (Li et al., 2025).

4.4. Other Starch Recoveries

Hydrogen can be produced from biomasses such as wastewater and organic waste discharged in the food industry and agriculture by microorganisms for which starch and glucose make excellent substrates. A major global environmental issue is the greenhouse effect, which is caused by rising levels of carbon dioxide in the atmosphere. Since burning fossil fuels releases significant carbon dioxide, it is desirable to develop alternative energy sources with minimal environmental impact. Because it can be readily transformed into electricity and burns cleanly, hydrogen is viewed as the perfect future energy source. Microbial hydrogen generation has been thoroughly studied among the various methods of hydrogen production because of its energy-saving nature (Yokoi et al., 2002).

Owing to its starch and curcuminoid content, turmeric rhizomes are commonly utilized as food ingredients. Extraction processes using supercritical fluid technology are widely applied to obtain high-quality extracts from turmeric rhizomes. However, these processes produce large amounts of waste. These wastes are potential sources of antioxidant components and carbohydrates. Mixed biopolymers consisting of starch and curcuminoids can be recovered by extraction processes using pressurized liquid ethanol and supercritical carbon dioxide. Recovered materials can be used in the industry as a matter for obtain color and as a source of resistant starch for human diets (Santana et al., 2017).

Fruit processing generates a lot of waste, including that from juice processing, jams, pulp extraction, and frozen pulp.

Wastes include shell, pulp, seed waste and pulp, which are rich in value-added compounds such as starch. It is estimated that 14.8% of total food waste generated comes from fruit/vegetable production and processing; in addition, approximately 50% of food waste in households comes from fruits and vegetables. (Kringel et al., 2020). Non-commercial starches based on fruit and vegetable waste can be used as alternatives to commercial starches in biodegradable film growth. The properties of starch obtained from these sources and their use as a biodegradable film are emerging trends in the field of packaging technology. To stop wasting valuable carbohydrates, especially starch, these resources need to be included in the concept of "circularity" and work towards more sustainable production practices. Additionally, enhancing the biodegradable film's composition is crucial for extending its barrier properties and shelf life (Sarma et al., 2024).

Biopolymers are a viable alternative to replace plastics with environmentally friendly materials. Despite its well-documented harms, plastic pollution is one of the leading causes of irreversible environmental damage today. This is due to the fact that a lack of recycling culture has led to landfills being overrun with tons of this disposable material. Biopolymer synthesis requires a natural polymer known as starch, a common compound in roots, tubers, fruits, grains, and aquatic plants. Starch from waste is a very good source for developing natural polymers and biopolymers (Sanabria et al., 2021).

Kitchen waste treatment and utilization are increasingly being treated with pyrolysis as a viable technique. Pyrolysis, a process involving thermal decomposition of materials in an anaerobic or oxygen-deficient environment, offers the advantages of minimal secondary pollution and high product reusability to produce oil, gas and coal. Extensive studies have shown that pyrolysis is an effective approach for solid waste treatment and has potential applications in handling various types of solid waste such as waste tires and waste plastics (Yao et al., 2024).

Depending on the variety, mango processing generates a large number of byproducts (peels and seeds) that make up 30 to 60 percent of the fruit's total weight. The mango seed consists of a fiber-rich husk surrounding the starch-rich kernel. 3D printed biopolymer parts can be obtained by reusing mango seed residue (Conceiçao et al., 2024).

Starch extraction from banana peel waste has the potential to utilize waste and obtain value-added products. Industrially packaged banana slices are produced in sweet and savoury varieties and the remaining peels are left as waste, and large amounts of post-harvest waste are produced during banana harvesting. These wastes mostly include partially green or unripe fruits, pathologically or mechanically damaged fruits, discarded fruits and leaf waste, stems, bunches and fruit peels. These wastes are very rich in starch. Starch can be recovered from banana and plantain waste for direct commercialization or other applications such as water treatment and polymerization. (Hernández-Carmona et al., 2017).

It was found that modified cassava starch waste can be used together with used coffee grounds in the development of a multifunctional gelatin-based hydrogel. Hydrogel has garnered a lot of attention for biomedical uses, like wound coverings. Injectable hydrogels hold promise for drug delivery and biomedical applications but often lack multifunctional properties such as antibacterial activity, self-adhesion, and controlled drug release. Cassava starch waste was used to prepare aldehyde starch, while ferric ions formed metal-ligand bonds with phenolic compounds extracted from coffee grounds. The resulting injectable hydrogel offers a promising approach to using food byproducts as a useful material for medical applications (Jittham et al., 2025).

The leaves and stems of pineapples become agricultural waste. The average weight of the stem remaining after peeling a pineapple is about 0.6 kg. Farmers typically dispose of this waste by burning and sun drying it, which is not good for the environment. Pineapple leaves are used in fibrous reinforcement of composite polymers. However, this renewable waste source can be a good alternative to obtain starch. Starch is a green alternative material and the most promising candidate for future use. This is due to its low cost, availability from renewable resources, and versatility for both food and non-food products. Pineapple stem starch can be obtained from pineapple stem only by wet milling. Starch obtained from waste has distinct and different properties compared to commercial starches (e.g. rice, corn and cassava). It has the more amylose content, which in turn results in the highest enthalpy of gelatinization, temperature of gelatinization, and temperature of bonding. Under normal cooking conditions, it has the minimum viscosity of paste. These properties will be advantageous for thermoplastic starch or resistant starch usage in food and non-food purposes, respectively (Nakthong et al., 2017).

Aimed to extract starch from cassava agro-industrial wastes, namely cassava peel and bagasse, as a non-edible resource, and developed an extraction method to maximize starch extraction from these sources. The properties exhibited by starch obtained from these sources suggest their potential applications as biodegradable food packaging matrices as an alternative to the spreadly used commercial cassava starch (Thuppahige et al., 2023).

5. OBTAINING STARCH FROM NEW SOURCES

Traditionally, starch is extracted from sources such as maize, potato, cassava as well as other minor sources such as cereals, tubers etc. and is utilized to enhance the functional characteristics of a variety of food and non-food formulations. The use of starches from unconventional sources as raw materials for commercial applications can provide an alternative to traditional starches that are laboriously produced, as well as reducing costs in industries.

The increasing demand for starch and the increasing awareness of the utilization of food waste as a potential source of starch have led researchers to extract and evaluate starch from various unconventional sources; this has led to studies on starches from grains, roots, tubers, seeds and even discarded parts of various fruits. Nowadays, new starches obtained from non-traditional sources attract great attention due to their different physicochemical and functional properties. New applications of starch are increasing steadily and attempts are being made to discover native starches that do not need any changes to achieve preferred characteristics for different uses such as syneresis, transparency, freeze/thaw stability in foods or mechanical strength and moisture sensitivity for making biodegradable films (Makroo et al., 2021).

Non-traditional sources of starch include fruits (unripe mango, unripe banana, unripe, sorted or wasted. These include apples, Jack fruit and seeds, Ramon), Rhizomes (Ginger, turmeric, lotus), cereals (Amaranthas, millet), pseudocereals (Buckwheat), Legumes (Lima beans, Kidney beans, Peas, Lentils), Nuts (Horse chestnut, Water chestnut. During industrial processing, inedible parts of non-traditional sources such as seeds, roots, stems, leaves and bracts are discarded. The high moisture content of these biological wastes makes them susceptible to microbial attack, resulting in environmental pollution. However, these biowastes are a rich source of starch as well as containing many bioactive compounds similar to those found in edible parts, including dietary fibers, sesquiterpenes, phenolic acids, lactones, flavonoids and enzymes. Starch can be recovered from its sources by different methods. Wet and dry milling are two main categories for extraction techniques. Although the dry milling approach is suitable, the recovered starch has poor functional properties compared to wet milling. The traditional approach to starch extraction (washing, cleaning from fat and protein, centrifuging and drying) is time-consuming and produces a large amount of waste containing high-quality compounds, therefore, new recovery methods necessarily be developed to get over the shortcomings of traditional methods. In this context, enzyme-assisted extraction has been widely used, such as starch recovery from rye grain using xylanase-protease. Alkaline solvents have also been used to dissolve the protein fraction to obtain extra pure starch, recently some new technologies have also been used for starch recovery such as supercritical carbon dioxide assisted starch extraction from turmeric waste. (Makroo et al., 2021).

There are many non-traditional sources of starch, but detailed information on the amount of starch that can be recovered is needed. Starch as a pure substance has wide applications, so starch recovered from different sources (native and modified) can be appropriate for a wide range of culinary and nonculinary uses. The use of starch can also be used in the formation of adhesives, filters and alcohols, but their applicability and practical effects depend on the properties of the starch obtained. The main application of starch is its use as an ingredient in various food products and formulations such as ice cream, confectionery, prebiotics, sauces, mayonnaise, ketchups, jams, puddings, fruit fillings for confectionery, canned meat and vegetables, yogurts or frozen foods and many more. However, starch also has many non-food applications; it is used in the pharmaceutical, chemical and cosmetic industries. Additionally, environmental issues associated with oil scarcity and petrochemical-based plastics have recently drawn worldwide attention to the development of biodegradable and environmentally friendly bio-plastics or edible coatings and films, in this context. Starch obtained from different plant sources has been found suitable due to its lower cost and processability with conventional plastic processing machinery such as injection molding and extrusion in the presence of plasticizers. In the pharmaceutical industry, starch is widely used in tablet formulations and capsule casings for drug delivery, similarly in the textile and paper industry, starch is widely used for multipurpose, recently due to the increasing concerns regarding natural gas and oil resources, starch has been studied for biofuel or ethanol production (Makroo et al., 2021).

6. CONCLUSIONS AND RECOMMENDATIONS

Starch is the primary component of many agricultural commodities, and it is one of the most boardly processed materials in the industry because it can be turned into a variety of food and non-food items. Starch is used to give the desired functional properties to the products. Starch is traditionally obtained from agricultural products such as corn, potatoes and rice. During starch production, wastewater containing starch is obtained from the process steps. In addition, during the processing of many grains, fruits and vegetables into other products, waste containing a very high amount of starch is produced. Disposing of waste is necessary for solving many problems such as legal obligations, protecting the environment and nature, transforming waste into valuable products, and being effective in the fight against hunger by preserving the food balance. Starch-containing wastes are recycled into valuable products for consumption as food, to create bioplastics, to produce lactic acid and ethanol, and to create biofuels. Instead of being evaluated as waste, methods that reduce waste generation during production should be applied and intermediate products containing valuable starch should be converted into by-products together. Thus, instead of solutions to waste and problems, waste-free industrial cycles should be established with combined systems. In this sense, starch is an important research topic for green industry as a valuable material.

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AQUAFABA: BY-PRODUCT OF THE CANNING INDUSTRY

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1. INTRODUCTION

There has been increasingly developed in the plant-based products market in recent years due to rising consumer concerns about the negative impacts of animal-based products on the environment/air pollution, animal welfare, and human health (McClements & Grossmann, 2024). Plant-based products can be products that imitate meat, milk and dairy products, such as soy meat, almond and walnut milk, or they can be directly derived from plant sources as a result of the preferences of vegans and vegetarians. Pulses are a good choice which are including dry bean, chickpea, faba bean, lentil, and dry pea because they have a low cost and high nutritional value and contain 20–30% lysine-rich protein (He, Meda, Reaney, & Mustafa, 2021; Solé Lamich, 2022).

In recent years, it has been observed that the demand for plant-based products instead of animal-based foods and/or animal-based semi-finished products has increased not only among the vegan population but also worldwide. This trend can be for health reasons as well as economic reasons. When considered in this context, both pulses (in terms of nutrition) and aquafabas (egg substitute) can be an important alternative. Aquafabas (pulse cooking water) are by-products of the canning

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industry that have the potential to be used in different areas of food technology, especially due to their protein content, with functions such as foaming, emulsifying and gelling. Plant-based proteins, which can replace animal-based proteins, have recently become the focus of attention due to reasons such as being an alternative to eggs against the risk of allergy, not containing cholesterol for health reasons, and being lower in cost. The vegan people tend to plant-based foods has also been influential in the emergence of aquafaba.

The proportion of individuals with a vegan diet preference in the general population has reached 12% in Canada, 11% in Australia, 30% in India, 18% in Sweden, 14% in Switzerland, 20% in the United Kingdom and 14% in Taiwan (Alsalman, Tulbek, Nickerson, & Ramaswamy, 2020). The increasing number of vegan consumers around the world makes it necessary to produce multifunctional additives and alternative food products for this product group. Thus, value-added products to which aquafaba is added will take their place among vegan products.

2. AQUAFABA HISTORY AND SOURCES

The cooking water of pulses was born in 2014 by French musician Joel Roessel and was tried in a different dessert recipe specific to abroad as a substitute for egg white. Roessel also stated that the foam stability of chickpea cooking water can be increased with starch and gums. Moreover, foaming properties were observed not only in the cooking water of chickpeas but also have been kidney beans. However, in subsequent studies, researchers stated that beans, lentils, broad beans and peas also have foaming properties. Then ıt was used in chocolate cream and meringue by Goose Wohlt who is a software engineer. Wohlt first named the pulse cooking water “aquafaba” on March

13, 2015. The word aqua refers to water, while faba is associated with the Latin family *Fabaceae*. After that, different posts about aquafaba were made on different social platforms and it took its place in academic studies in 2017 (He, Meda, et al., 2021). Aquafaba is obtained not only from chickpeas but also from other pulses; beans, kidney beans, broad beans, lentils, pea species and also soybean used in literature. These legumes are generally used in the three-stage canning process. First of all, the soaking process is necessary so that the legumes can be cooked well in a short time. Then, while the legumes are boiled, at the same time aquafaba production also takes place. Lastly sterilization at 121 °C for 15. According to the industry procedure all pulses cooked at 95 °C for different times to obtain aquafaba. (Kilicli & Toker, 2022).

3. AQUAFABA COMPOSITION

The inclusion of aquafaba, which is a new subject in the literature, in academic studies began with the research (Stantiall, Dale, Calizo, & Serventi, 2018) used various aquafaba. Studies have shown that aquafabas have various technological features such as such as emulsifying ability, foaming capacity and gelling ability. Their finding that aquafabas have foaming capacity between from 39% to 97%. Authors reported that it was observed that green lentil has the highest foaming capacity. Researches on the physicochemical features of aquafaba, its modification and its use in some foods are about to complete their first decade.

Table 3.1 shows the aquafaba compositions of different pulses. Different dry matter contents, different boiling processes (temperature, time, etc.) in obtaining aquafaba or using cooking water in the last stage of canning production (sterilization) cause higher values. In addition, since some studies focused on hummus, the boiling or cooking parameters may have been quite high, leading to an increase in dry matter and other components. Take into consideration at the dry matter content, carbohydrates, fibers, protein and ash have been reported in many studies. Moreover, saponin is also present along with protein, which affects the foaming properties. In our previous study (Kilicli & Toker, 2022), we investigated the physicochemical properties of chickpeas, beans, green lentils and peas, kidney beans and broad beans. In the study, aquafabas were concentrated and the brix values were equalized at 10. Dry matter contents varied between 10% and 12%, while water content was more than 90% in many studies (Solé Lamich, 2022), probably because of the lack of evaporation process. The dry base consists of carbohydrates high ratio and secondly of aquafaba proteins. The dry base consists of carbohydrates high ratio and secondly of aquafaba proteins.

When studies on aquafaba began with chickpeas, the concept of aquafaba became synonymous with chickpeas and studies were generally focused on chickpeas. However, in our study, the lowest protein content (22%) on a dry basis was obtained in chickpeas. The highest protein content was obtained in green peas and lentils with 34% and 31%, respectively. However, the foaming properties of green peas and lentils are similar, the boiling smell in lentils is not as suitable for the products as green peas. Therefore, aquafaba obtained from green peas will be more suitable in products both in terms of unwanted odor compared to lentils and due to its higher foaming capacity depending on the amount of protein (Kilicli et al., 2025; Kilicli, Erol, Toker, & Tornuk, 2022; Kiliçli, Özmen, Bayram, & Toker, 2023).

The total phenolic and tocopherol content of aquafaba has been reported in several studies. However, it has been stated in the study that some antinutritional factors such as phytic acid and tannin may be in the content of aquafaba. However, it has been stated that some of the antinutritional elements may migrate into the soaking water (Frias, Vidal-Valverde, Sotomayor, Diaz-Pollan, & Urbano, 2000) and some may become inactive during boiling (Adsule, Lawande, & Kadam, 1989). In addition, studies have shown that low concentrations of some components regulate blood cholesterol and blood sugar, and some oligosaccharides such as raffinose and stachyose function as prebiotics (Chen, Singh, Bhargava, & Ramanathan, 2018).

Aquafaba in its liquid form is not suitable in terms of both microbial quality and shelf life. Therefore, it would be more appropriate to store it in powder form or as a concentrate. And also, some researchers have stated that aquafaba in powder form exhibits better functional properties (ASLAN & ERTAŞ, 2020; He, Purdy, et al., 2021).

Table 3. 1 Aquafaba composition of different pulse cultivar

Aquafaba species	Dry matter (g/100g)	Water soluble LMWkh (g/100g)	Water soluble HMWkh (soluble fibers)	Insoluble fiber (g/100g)	Protein (g/100g)	Ash (g/100g)	Saponin (mg/g)	Dietary fiber (g/100g)	Total phenolic (mg/g)	Tocopherol (µg/mL)	Tannin (mg/100g)	Phytic acid (g/100g)	Reference
Bean	3.28	0.73	0.16	0.93	0.70	0.75	5.9	-	-	-	-	-	(Stantiall et al., 2018)
Chickpea	5.13	1.20	0.04	2.37	0.95	0.57	4.5	-	-	-	-	-	
Green lentil	4.69	0.54	0.07	2.09	1.51	0.48	12	-	-	-	-	-	
Broken yellow peas	4.41	1.02	0.09	1.63	1.27	0.40	4.7	-	-	-	-	-	
Yellow soybeans	5.59	1.66		2.46	0.68	0.78	6.4	-	-	-	-	-	(Serventi, Wang, Zhu, Liu, & Fei, 2018)
Chickpea	5.03	3.28		-	1.27	0.44	-	0.69	6.50	0.11	-	-	(Raikos, Hayes, & Ni, 2020)
Chickpea	7.89	-	-	-	1.3	-	-	-	-	-	-	-	(Buhl, Christensen, &

													Hammershøj, 2019)
Chickpea	5.8	1.2		2.4	0.95-1.5	0.6	4.5-30	-	0.6	-	-	-	(Mustafa & Reaney, 2020)
Chickpea	4.9-6.4	-	-	-	1.21-1.72	-	-	-	-	-	-	-	(Shim, Mustafa, Shen, Ratanapariyanuch, & Reaney, 2018)
Chickpea	-	-	-	-	0.5-1	-	-	-	-	-	0.49–11.8	0.000-0.057	(Alsalman et al., 2020)

4. FUNCTIONAL PROPERTIES OF AQUAFABA

Aquafaba, a by-product of recent years, has technofunctional properties such as foaming, emulsifying and contributing to gelation. It is emphasized that these functional properties are due to the proteins, soluble and insoluble carbohydrates, saponins, polysaccharide complexes and phenolic compounds found in aquafaba (Serventi, 2020). Studies conducted so far have mostly focused on foaming and emulsification, and there are very few studies on gelation. While water-air interaction is important in foaming, water-oil interaction is effective in emulsification (He, Meda, et al., 2021). Aquafaba proteins, which are amphiphilic character, have hydrophilic and hydrophobic groups. Hydrophilic groups interact with water, while hydrophobic groups interact with air/oil phases. As a result of these interactions, the surface tensions at the air/water and water/oil interfaces decrease, and the folded structure of the proteins opens with the encouragement of mixing (for emulsion) and whipping (for foaming), and the homogeneous mixture of water and oil on the other hand, and the proteins trap air molecules inside. Finally, a stable emulsion and foam are formed (Klamczynska, Czuchajowska, & Baik, 2001; Mariotti, Pagani, & Lucisano, 2013; Wu, Clifford, & Howell, 2007).

Aquafaba proteins are generally low molecular weight species (≤25 kDa), that have notable surface-active and foaming properties like albumin (Shim et al., 2018). In our previous study, proteins in green pea aquafaba were observed to be more concentrated below 30 kDa (Kiliçli et al., 2023). In addition to proteins, saponins also contribute to foaming and emulsification. Saponins can be regarding as non-ionic surfactants because of their amphipathic form which is concluding a lipid-soluble part and water-soluble part. Therefore, researchers assumed that saponins can reduce tensions at the oil-water and air-water interfaces as an emulsifier between phases. So that saponins assist to form foaming or stabil emulsion (fat globules) (Chung, Sher, Rousset, Decker, & McClements, 2017; Güçlü-Üstündağ & Mazza, 2007). Moreover, the interactions of phenolic compounds not only polysaccharides but also proteins can affect their emulsify and foaming ability (Vega & Grover, 2011; Wu et al., 2007).

While the technofunctional properties of aquafaba originate from by the topics explained above (primarily protein, saponin, phenolic components), the methods of produce aquafaba are undoubtedly too effective. Generally, the technological characterisation of aquafabas are affected by two factors depending on its composition. First of all, the cultivars (chickpea, bean, kidney bean, lentil, pea etc.) and species of pulses (kabuli chickpea, koçbaşı chicpea, etc.) and also seed and cell wall composition, environmental conditions, storage conditions. Secondly, extraction conditions; soaking, cooking types (boiling, pressure cooking, steaming and canning), and cooking parameters (time, pressure, water to seed ratio, temperature), pH and additives (salt, EDTA etc.) (Erem et al., 2021; He, Meda, et al., 2021; Mustafa & Reaney, 2020).

Crawford, Tyl, and Kerr (2023) investigated the functional properties of aquafabas by producing with chickpeas at different water-to-seed ratios (3:1, 4:1 and 5:1) and pH (3, 5, 6 and 7) under different cooking (boiling and pressure cooking) conditions. They found the highest foaming capacity as 181% at water-to-seed ratio 5:1, pH:6 under boiling at 100 °C for 1 hour. And also, the highest emulsion activity calculated as 76 m^2/g water-to-seed ratio 3:1, pH:3 under boiling at 100 °C for 1 hour. The xanthan gum who used played a more effective role than HPMC (hydroxypropyl methylcellulose) and contributed to the foam stability by preventing liquid drainage for 24 hours.

In another study, the effect of different extraction parameters on the composition and foaming of aquafaba investigated by Choden et al. (2023). The chickpea to cooking water ratio (1:1, 1:1.6, 1:4), cooking temperature (60, 80, and 100 °C) and time (90, 165, 240 min) was determined. They found maximum foaming capacity (FC) was observed at 80 °C, chickpea to cooking water ratio of 1:1.6, and a time of 165 min. And also foam stability not effected significantly in all extraction conditions. Kargar and Sourki (2024) have used microwave in the soaking process before aquafaba production. Process conditions was microwave power from 360 to 900W and irridations time between 5-15 min. Optimal extraction was determined for 5 min of irradiation at 900 W. The findings has shown that increased microwave irradiation time led to a reduction in foaming ability and extraction efficiency but also significantly improved the soluble protein content and foam stability of aquafaba.

In our previous research (Kilicli & Toker, 2022) , we soaked 6 various legumes (white bean, Chickpea, green pea and lentil, broad and kidney bean) using ultrasonic and traditional methods. Ultrasonic method shortened the soaking time by helping moisture diffusion in the channels formed by the effect of vibrations. According to industrial canning process pulses were cooked at different temperature and time as pulse/water

(1:1.5). Microscopic images of aquafaba and foam were presented in Figure 4.1. Clearer aquafabas were obtained, probably due to the effect of ultrasound on the structure. As regarding this foam consideration, green pea and lentil foams highest foaming capacity resulted from has small bubbles size. Moreovers small bubbles has exhibited more stable form for foam stability. The foaming properties (foaming capacity and stability) of traditional soaking changed between 167 -567% and 74–95.8%, respectively. As for ultrasonic soaking with a little reduction between 133-533% and 70–98%, respectively. Protein content of aquafaba obtained from legumes soaked with ultrasound was lower. This is probably due to the transfer of protein into the water due to the effect of ultrasound during soaking. Among the study results, there is a direct proportion between foaming properties and protein content. Similarly Stantiall et al. (2018) found this positive correlation. Front and top views of aquafaba bubbles were shown in Figure 4.2. While the lowest resistance against to gravitational force to white bean and chickpea aquafaba, highest resistance to green pea and lentil was also observed in pictures, verify the findings of foaming properties. Although pea and lentil aquafaba have similar foaming properties, pea aquafaba has a higher foaming capacity and stability than lentil, which brings pea to the forefront for both modifications and product use. In addition on the contrary of lentil aquafaba; pea aquafaba do not contain any unwanted odors caused by boiling, which makes them more advantageous, especially in terms of products.

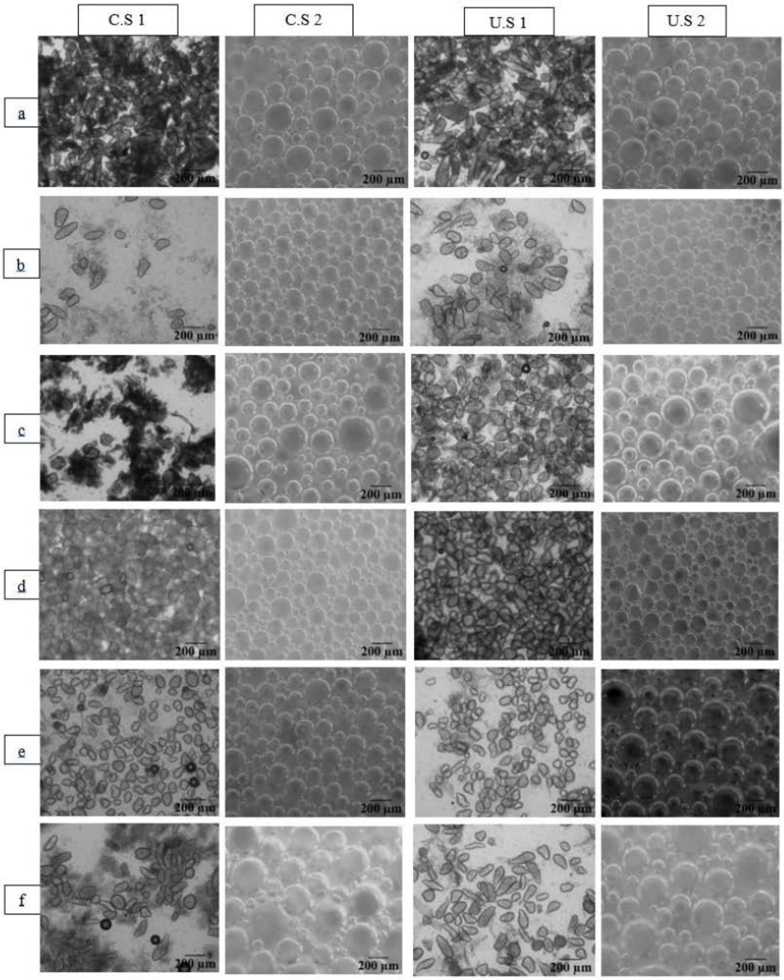

Figure 4. 1 Microscopic images of aquafaba and it's foams ((CS-1.2 Traditional aquafaba and its foams, US-1.2 Ultrasound aquafaba and its foams, (a: broad bean, b: green pea, c: kidney bean, d: green lentil, e: kidney bean, f: chickpea).

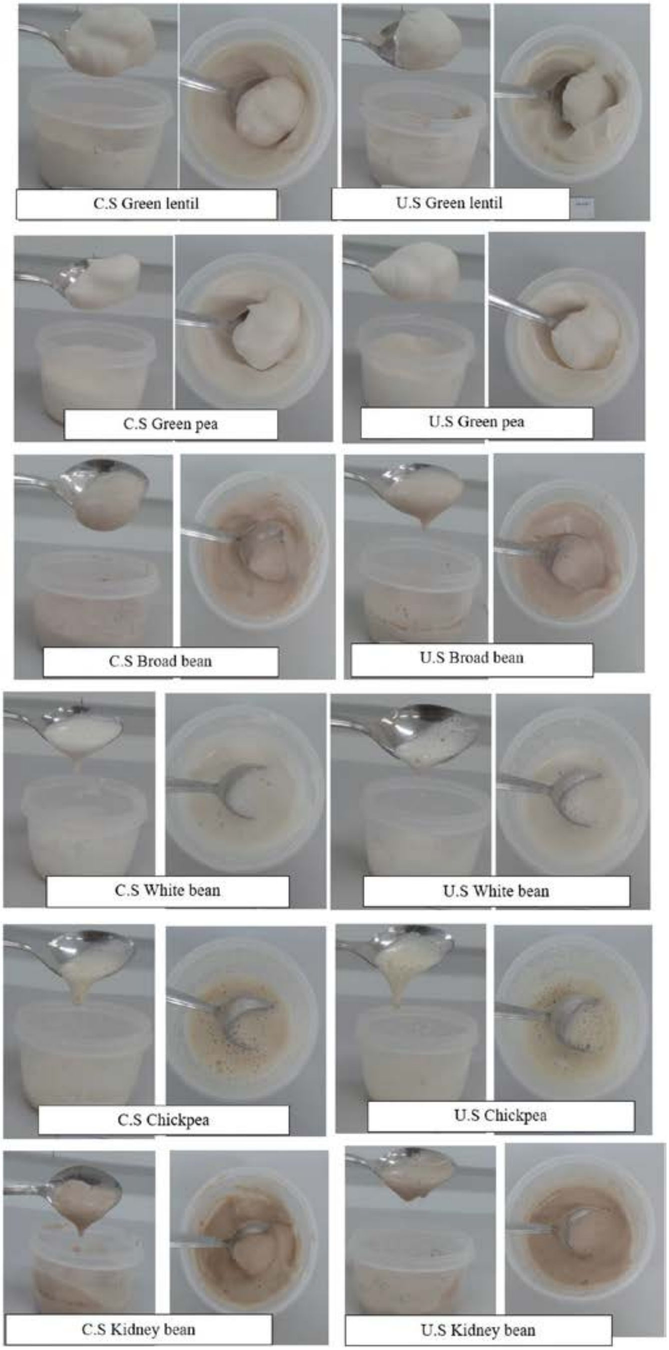

Figure 4. 2 Front and top views of aquafaba bubbles.

5. IMPROVING THE FUNCTIONAL PROPERTIES OF AQUAFABA

The technological properties of aquafaba and replace egg white for vegan products provided encouragement of investigation focused on enhancing the techno-functional features of aquafaba. We can generally collect these studies under three topics (ultrasound, high pressure and fermentation).

The first study by Meurer, de Souza, and Marczak (2020) investigated affects of ultrasound on chickpea cooking water. Ultrasound treatment increased foaming capacity from 259% to 548% at the 100% power for 30 min as well as foam stability. And also has been reported an enhanced to emulsifying ability of aquafaba and textural properties of foams and meringue. In addition, including 100% power and 10 minutes of ultrasound, the foams resisted gravity force and resulted from smaller air bubbles confirm to more foam capacity and stability.

Kim et al. (2022) examined quality characteristics of plant-based mayonnaise using chickpea aquafaba with different ultrasonic treatment time. While protein solubility increased with ultrasound application, emulsion activity exhibited better results in 30 minutes instead of 60 and 90 minutes. The size of oil droplet decreased by ultrasound and lower only 7% than consisting of egg yolk based mayonnaise in terms of emulsion stability.

Noh and Lee (2024) has investigated effects of ultrasound on the aquafaba extracted from different pulses. The highest emulsifying properties has been observed in the small black bean sonicated for 40 min. With increasing sonication time, particle size decreased while hydrophobic amino acids increased significantly. While zeta potentials increased in all pulses, the least undesirable pulse flavor has been observed in chickpeas and small black beans.

Roosta and Sourki (2024) has studied with black chickpea aquafaba treatment with ultrasound before aquafaba processing. They have found that aquafaba yield and protein solubility increased with increasing sonication time and amplitüde significantly. For the best foaming properties, high amplitude and short duration treatments were more effective. According to numerical optimization, the best condition was found to be 30 minutes of ultrasound treatment at 72% amplitude.

It has been reported that it contributes to emulsifying properties in studies conducted at high pressure. And also it has reduced protein aggregation while increasing the consistency coefficient and therefore the storage modulus G' resulting in a more cohesive gel network (Alsalman & Ramaswamy, 2021a, 2021b). High pressure increased foaming stability by 34% and significantly improved the consistency coefficient. It also resulted in brighter color and reduced particle size. (Alsalman, Al-Ruwaih, Al-Attar, & Mulla, 2022).

Begliyev, Yavuz, and Ok (2023) in order to the aquafaba, which they dried with a spray dryer, to gel, they prepared a concentration of at least 20% and applied 120 Mpa. While the highest viscosity was obtained at this pressure, the storage modulus was 7-9 times higher than the loss modulus.

Mehren, Elliger, May, Schieber, and Schulze-Kaysers (2025) have used fermented chickpea aquafaba in vegan chocolate mousse. Fermentation of aquafaba enhanced foaming capacity at the same time reduced beany aroma of chickpea aquafaba in product. Chocolate mousses, which were highly accepted by consumers, has exhibited a slightly porous, soft and melting structure.

Bekiroglu et al. (2023) have improved techno-functional properties of aquafaba powder by pre-fermentation using *Lactobacillus plantarum*. While 9 hours of fermentation was applied for foaming capacity and stability, 3 hours of fermentation gave optimum results for emulsion. Colucci Cante et al. (2025) has researched lactic acid fermentation applied to aquafaba, emulsion capacity increased 10-fold, while foaming and emulsion stabilities approached 100%. In addition, a significant increase in antioxidant activity was observed after fermentation, while it was also emphasized that fermented aquafaba could be a probiotic and texture-improving component.

6. AQUAFABA BASED COMMERCIAL PRODUCTS

Generally, it can be said as a common result of the studies that aquafaba can be substituted for egg white, but mixing it with egg white in certain proportions can give better results. However, as Joel Roessel stated, in vegan products, it is possible to obtain technologically more qualified products by making the foam stability more stable with starch and vegetable gums. So far, aquafaba have been used in which require foaming and emulsion, such as especially cakes and mayonnaise, meringue, whipped cream, sorbet, ice cream, chocolate sauce.

Mustafa, He, Shim, and Reaney (2018) studied with aquafaba as an egg substitute in sponge cake. The filling liquid of 10 different canned chickpeas was used as aquafaba and the aquafaba with optimum foam properties was evaluated in the cake. The findings showed that aquafaba can be used in cake product. Silva, Kalschne, Salvati, Bona, and Rodrigues (2022) tried to develop a plant-based powder that could replace egg. Their finding mixtures consist of approximately 68% of powder aquafaba, 20% of lentil protein, and 12% of citric acid were acceptable for gluten free cake as an egg replacer. Crawford, Kerr, and Tyl (2024) researched hydrocolloid addition on cake prepared with aquafaba. While xanthan gum did not lead to a desirable crumb structure on the cake, 0.2% hydroxypropyl methylcellulose increased the volume index to a level comparable to the cake sample containing egg white.

Serventi et al. (2018) investigated the emulsifying effect of soybean cooking water on gluten-free crackers was investigated. It was found that aquafaba significantly prevented hardening of crackers during storage. It was emphasized that soybean cooking water is a functional ingredient in terms of mineral content and also has a potential effect on improving texture.

Buhl et al. (2019) examined the emulsion and foaming features of aquafabas obtained from different canned chickpeas, they also determined parameters such as protein-based SDS-PAGE and zeta potential. In this context, it was emphasized that aquafabas form a more stable emulsion than egg whites, and it was determined that they have the potential to substitute egg whites in terms of foaming capacity.

Raikos, Hayes, et al. (2020) used aquafaba as an egg yolk substitute for the first time in mayonnaise. In this study, the possibilities of using aquafaba in mayonnaise production were determined by examining both its optimization for vegan production and its storage stability. Low aquafaba oil content a/o ratio (15/80%) was the most suitable option for the smallest droplet size distribution. While the oxidative stability unaffected during storage the authors stated that aquafaba can be used to egg substitute in mayonnaise formulations containing oil at standard levels. Jeong and Oh (2025) prepared vegan mayonnaise with peanut sprout oil and aquafaba. Aquafaba-to-oil ratios (33:60) exhibited the most desirable characteristics, including firmness and physical stability comparable to egg-based mayonnaise as well as sensory properties. This formulation exhibited highest oxidative stability, and the lack of egg yolk did not increase lipid oxidation.

Raikos, Juskaite, Vas, and Hayes (2020) produced oat-based yogurt using aquafaba as a gelling agent. Yogurt stored 3 weeks under refrigerate. They found that aquafaba decreased syneresis and increased water holding capacity during storage as well as improve of hardness.

Kilicli, Erol, Toker, and Tornuk (2023) produced tomato powder using green pea aquafaba. Thanks to the porous structures, drying ended shorter time at high temperature and at the same time the bioactive components are less damaged. In another different study Kilicli et al. (2025) produced to sorbet with persimmon using green pea aquafaba. The use of up to 15% aquafaba provided approximately 50% overrun in sorbet. Improvements in protein, dietary fiber, brightness, phenolic content and sensory properties were observed with increasing aquafaba content.

Take into consideration, the studies conducted, the evidence of the potential use of aquafaba in different products is increasing day by day. With the potential of aquafaba being used in different products, it has found its place in the commercial market under different brands in concentrated or powder form (Oggs, Vör, Vegg etc.) both in our country and abroad.

7. CONCLUSION

Aquafaba, which was seen as a waste of the canning industry but has been transformed into a by-product and used in value-added products for the last decade, is increasing its popularity day by day. Both the use of aquafaba in different products and its commercialization have brought about the development of its functional properties with different technologies. In addition, the interest in plant proteins, which has been a trend in recent years, makes aquafaba even more important.

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VOLARIZATION OF POTATO PEEL WASTE: AN OVERVIEW

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1. INTRODUCTION

Especially in developed nations, people need more convenient foods in the kitchen owing to the necessities of fast living and on-the-go diet. For this reason, while the use of potatoes in different forms such as frying, fast food and fighting is increasing, the use of fresh potatoes is decreasing. In addition, a great amount of by-products are created every year during the industrial manufacture of foodstuffs such as potatoes. Studies on the purification of these by-products and remains have been increasing continuously in recent years. In potato, which is an essential industrial product, the by-products that arise after the production phase are as follows: peel, pulp, potatoes not suitable for processing, and wastewater. In starch production, pulp is also produced from raw potatoes.

Potato (Solanum tuberosum L.) is a global common human food and is consumed as a basic food in many nations.

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Potato bio-diversity consists of more than 4000 species, among which 200 types of both wild and crop varieties [1],[2].

The dietary components of various potato varieties contain the following (Fig.1.): fat, carbohydrates, protein, fiber, vitamins, minerals, physicochemical compounds, phenolic compounds, carotenoids, organic acids and glycoalkaloids.[1],[3]. The discharge of this pulp from treated potatoes into the environmental environment will increase the pollution of the environment.[4], [5].

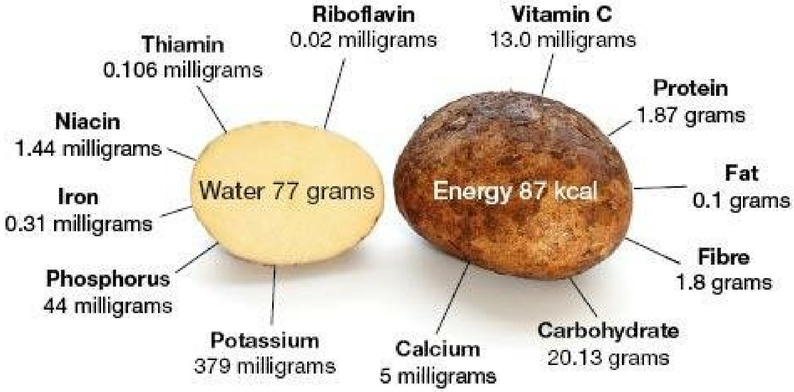

Figure 1. Chemical composition and nutrient content of potato [6]

Potato, which is an extremely important nutritional supplement in human diet, is of particular significance in terms of its rich composition. It is significant for humans in developed countries due to its rich content of starch, vitamin C, and potassium. It is a rich supply of essential nutrients such as carbohydrates, protein, vitamins, minerals and micro-nutrients that are essential for human growth and human metabolism [7].

Potatoes have a high nutritional advantage among all food products due to their extremely high biological content. It also contains iron and magnesium. Calorie, protein, mineral and vitamin levels of raw and processed potatoes are shown in Table 1.

Table 1. Chemical Composition of Potato Tubers [8]

Component	Content (%) Average	Range
Dry matter	23.7	13.1–36.8
Starch	17.5	8.0 –29.4
Reducing sugars	0.3	0.0-5.0
Total sugars	0.5	0.05-8.0
Crude fiber	0.71	0.17-3.48a
Pectic substances	-	0.2-1.5
Total nitrogen	0.32	0.11-0.74
Crude protein	2.0	0.69-4.63
Amide nitrogen	-	0.029-0.052
Amino acid nitrogen	-	0.065-0.098
Nitrates	-	0.0-0.05
Lipids	0.12	0.02-0.2
Ash	1.1	0.44-1.87
Organic acids	0.6	0.4-1.0
Ascorbic acid and dehydroascorbic acid (mg/100 g)	10-25	1-54
Glycoalkaloids (mg/100 g)	3-10	0.2-41
Phenolic compounds	-	5-30

2. MATERIALS AND METHODS

In the review study, 40 journals were examined, 60% of the journals were directly related to research studies on potato peel and 40% of the journals were made by screening studies on food waste. In overview, the most current state of literature on potato residues and their organic nature has been summarised.

3. UTILIZATION OF POTATO PEEL

Both synthetic and natural anti-oxidants are used in the industry; but application of synthetic protectants has potential cancerogenic impacts, so the use of natural preservatives alone is more important for human health with reduced negative side effects. For this reason, plant residues, which are rich phenol sources, have attracted much attention lately[9],[10]. Phenolic substances are found everywhere in plants. They attract attention with their anti-oxidant and anti- bacterial and anti-microbial features[11].

In the industrial food industry, between 70 and 140 thousand metric tons of potato skins are manufactured worldwide per year [12].

Potato peel, a by-product of the food refining industry, is of major significance from an economic point of view. It is a valuable and reasonably priced inexpensive starting material for food fibre, biopolymers, antioxidants, naturally occurring antioxidants and additives [13].

It is traditionally used as a valuable fertiliser and biogas feedstock for low-cost livestock farming, wasting excess nutrients with anti-oxidant, anti-bacterial, chemical and anti-inflammatory effects. [14]. Although, potato peel has been the most suitable waste treatment with the economic viability of processing enhancement [15].

Many research studies have been carried out time to time on the potential role of potato peelings in several industrial applications, demonstrating their potential as natural food preservative, animal feed, biofuel production, biodegradable packaging material, and even as medicine. This review synthesises the latest research on the composition, bioactive properties and applications of potato peel, promoting the continued use and industrial uptake of potato peel.

4. COMPOSITION OF POTATO PEEL

In view of the complete physicochemical characteristics of potato peel, it must first be formed. Being aware of these characteristics will help to develop an eco-friendly concept for the utilization of potato peel. The chart below gives an overview of the main nutrient constituents based on a review of a recent review of the available literature (Table 2).

The composition of the various nutrients contained in potato skins varies depending on the location of geographical areas of cultivation and on the composition, variety, color, and type of potato (and hence of the skins) [16],[17]. The compositions of potatoes are dependent on potato cultivars as well as several other factors such as type and temperature of soil, position, cultivation practices, ripeness and post-harvest storage requirements.

Potatoes mostly consist of water (about 80 per cent) and 20 per cent dry matters. Potato peel contains a wide variety of major macro-nutrients, biologically important nutrients, bioactive substances, bioactive compounds and dietary fibres. Potato peel also contains abundant amounts of (25%), non-variable polysaccharides (30%), protein (18%), acid-soluble and acid-insoluble lignin [18]. It also contains potato peel particles. These components are starch, cellulose, hemicellulose and other reducing sugars [18],[19].

Table 2. Chemical composition of potato peel

Potato peels(PP) varieties	Moisture %	Protein%	Fat%	Ash%	Fiber%	Carbohydrates%	Referances
Mexico White PP	4.95 ± 0.17	14.41 ± 0.82	-	8.07 ± 0.11	15.02 ± 0.58	52.80 ± 1.18	[20]
Mexico PP(*S. tuberosum L.)*	5.27± 1.74	9.11± 0.42	2.26± 0.64	3.11± 0.23	-	80.25± 1.71	[21]
India PP*(S.tuberosum L.)*	7	14	1	2,5	-	79	[22]
India Coarse PP*(S.tuberosum L.)*	5.620±0.022	9.368±1.177	1.550±0.957	4.805±0.910	-	74.473±1.368	[23]
India Fine PP*(Solanum tuberosum L.)*	6.397±0.258	8.697±0.041	1.883±0.968	4.600±0.327	-	76.789±1.340	[23]
Bangladesh Cabinet PP*(S.tuberosum L.)*	7.61 ± 0.01	11.38 ± 0.07	7.23 ± 0.12	9.64 ± 0.67	12.93 ± 0.09	55.43 ± 0.01	[24]
Bangladesh Sun PP*(S.tuberosum L.)*	10.27 ± 0.15b	9.33 ± 0.45	6.71 ± 0.41	10.39 ± 0.21	12.40 ± 0.16	50.49 ± 0.67	[24]
Romania PP*(S. tuberosum L.)*	5.57± 0.89	11.42±1.39	1.36±0.40	5.96± 0.62	13.76±1.20	64.82±3.81	[25]
Nigeria Irish PP	9.90 ± 0.02	4.54 ± 0.06	1.65 ± 0.02	3.67 ± 0.01	4.81 ± 0.03	67.89 ± 0.02	[26]
Netherlands Agata PP	5	4	1	8	29	53	[27]
India PP	6.32 ± 0.10	13.15 ± 0.41	1.25 ± 0.04	7.89 ± 0.10	13.05 ± 0.09	71.39 ± 0.30	[28]

5. PHYTOCHEMICALS AND VITAMINS-MINERALS IN POTATO PEEL

Potato peel contained various antioxidant substances such as phenolic acids and various polyphenols, while fatty acids and lipids also showed some antibacterial activity [14].It appears to have an important role in the options for protecting against pathogens and is therefore rich in nutritional vitality. About 50% of the phenolics are therefore found in the peel and associated tissues and are reduced in the centre of the tuber[29].

Potato peel biological polyphenols can reach almost triple the antioxidant activity compared to other plant tissues. The total content of phenolic compounds in PPW differs between potato varieties and is a varied class that can be categorised as phenolic acids and flavonoids. Phenolic acids are the major phenolic components in potato. Of all these phenolic acids, caffeic acid and quinic acid ester, chlorogenic acid and chlorogenic acid ester were detected significantly in potato [30]. In particularly, chlorogenic acid is by far the richest phenolic ingredient and accounts for 90% of the total phenolics.

Potato peel also includes flavonoids, glycoalkaloids and caratenoid compounds. These compounds play an essential role in inhibiting and preventing food oxidative stress and enhancing food preservation.

The flavonoids in potato peel are:

- Quercetin
- Naringenin
- Catechin
- Epicatechin

Quercetin, a flavonoid found in potato peel, has potent anti-inflammatory properties and properties of antioxidants that protect body cells from free radical attack.

The anthocyanins in potato are composed primarily of cyanidin and pelargonidin (red varieties) or petunidin, peonidin and malvidin (purple varieties) glycosides, Purple Majesty and Rio Grand are rich in both anthocyanins and contain carotenoids, xanthophylls, lutein, etc. They show potent anti-oxidative activities, influenza virus activity and anti-gastric cancer activity. Glycoalkaloids are components that are found naturally in common potato varieties and in small quantities contribute to the classic flavour of the potato. High amounts of glycoalkaloids in potatoes impart a strong bitter taste and can lead to illness or discomfort Common carotenoids are one of the principal lipophilic components that contribute to the total anti-oxidant activity and provitamin composition of potato. Potato peel powder has a high content of carotenoids, 135.76 mg/g DW. The nutraceutical values of vegetable by-products are used as food components and cause lower environmental pollution [31].

Varying quantities of potassium, iron, riboflavin, and folate as well as vitamins are primarily found in the dense potato periderm (Fig. 2). It is seen that the content of some minerals is higher in the soft skin of the tuber than in its pulp.

Since the fiber, vitamin C and vitamin B-6 content of the potato is combined with its deficiency, it has good heart support.

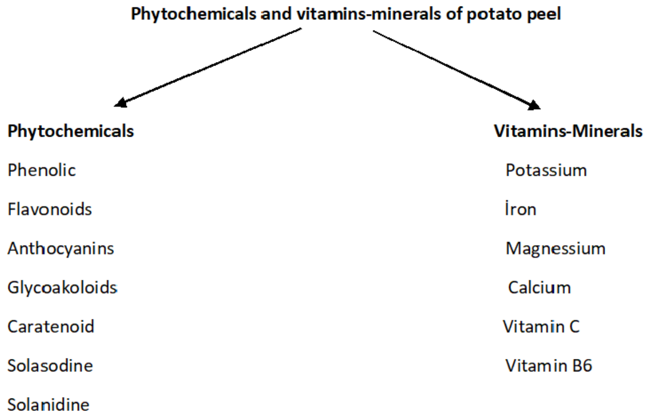

Figure 2. The figure indicates the phenolics and vitamin -minerals of potato peel

6. APPLICATION OF POTATO PEEL IN THE FOOD INDUSTRY

The literature study of the past five years on the use of potato peel in various types of food products such as bakery, pasta, cakes, noodles, biscuits, etc. is given in Table 3.

Table 3. Application of Potato Peel in the Food Industry

Foods	Amounts of Potato Peel	Important Results	References
Potato Foam	138.5 gr	In the sensory analysis, it was determined that potato foam was accepted with a high score. When the color values were examined, the most popular foam sample was potato foam.	[32]
3D printed noodles	40%	3D printed noodles developed with potato peel have a very good cooking quality and textural properties comparable to the commercial sample	[23]
Beef patties	2.0%	Adding potato peel rise b* value, hardness, cooking efficiency, and moisture eclipse but decreased springiness, and co hesivity	[33]

Bread	2.5, 5.0 and 7.5%	Sensory acceptance of the formulation with 5.0% potato flour content was higher.	[5]
Cake	4, 6 and 8%	The addition of PPF increased the height, volume and weight of cakes compared to the control (100% wheat flour) cakes. In the sensory evaluation, the cakes enriched with 4% PPF achieved thehighest score for the sensory attributes.	[24]
Waffle Ice Cream Cone	5,10 and 15%	A 5% formulation of the sweet potato skin fibre flour (SPPF) resulted in the maximum friability of the waffle bars.	[34]
Biscuit	3, 5, 7, 10, 30, and 50%	The 3% and 5% replacement rates contributed to improving most organoleptic characteristics (general acceptability, color, taste) compared to the samples with the highest studied percentages (30% and 50%). Although the highest percentages of PPP addition led to lower scores for sensory characteristics	[35]
Jelly	10 and 15%	It was observed that in case of jelly value addition at 15% incorporation level with the potato peel powder was the best product acceptable in the sensory evaluation. Jelly were rich in cabohydrates, fibres and energy	[36]
Fried chips	0, 2, 4, 6, 8, and 10%	Sensory evaluation revealed that the chips with PPF (by 10%) were more preferred	[37]
Prebiotic Yoğurt	2%	Higher titratable acidity and lowerpH was the reflect of the prebiotic capacity of both peel flours, with no detrimental effect on consumer acceptance	[20]
Melted cheese	0.5 and 1 gr	Consumer acceptability of the products was assessed by textural and sensory analysis. During the whole storage period, the samplesof melted cheese with potato peels recorded higher values than the control sample	[38]
Fabricated potato snack	0, 1. 5, 3, 4. 5 and 6%	The ready-to-eat snack developed can be categorized as 'low-fat' and 'good source of fiber'.	[39]
Pork patties	2,5 and 10%	Adding potato peel powder to pork raw dumplings can reduce pH, lipid oxidation, lipid metabolism, water storage capacity, weight and cooking loss. color readings during storing.	[21]

7. BENEFITS OF POTATO PEEL IN DIFFERENT INDUSTRIES

Potato peel is rich in high amounts of water, fiber, vitamins, proteins, minerals such as potassium, magnesium and iron, and carbohydrates. It contains potential bioactive compounds such as PP, antioxidants and flavonoids, [40]; [41] making it a valuable ingredient for the health and herbal medicine industry. Potato peels also contain starch, are low in calories and contain almost no fat. Starch can be used in the production of biodegradable plastics. Greater use of peels and surplus potatoes that do not reach the market or production will make bioplastics production more sustainable. Potato peels can be preferred as an ingredient in the cleaning industry as they contain solanine, one of the glycoalkaloids. Therefore, a biological detergent made from potato peels can be used to remove grease stains from clothes or to clean carpets and stainless steel surfaces. The starch contained in potato peels also causes a pilling effect that protects against new soiling. Potatoes and their skins also contain oxalic acid, also found in chemical cleaning agents, which can dissolve rust and limescale.

Potato peels can be used not only in the cleaning sector but also in the cosmetic sector. Thanks to the vitamins it contains, it can be processed into hair care products that strengthen and make hair flexible. In addition, vitamin B regulates the activity of the sebaceous glands that secrete oily secretions to the surface of the skin, making the hair shiny. It has been reported that blonde hair darkens slightly with regular use.

Potato peels also contain antioxidants, antibacterial compounds and phenols and have a skin-whitening effect. In this way, it can be used to lighten dark spots such as dark circles under the eyes and create a balanced skin tone. In addition, cosmetic products made from potato peels can moisturize the skin while absorbing excess oil, which is the most common cause of skin blemishes. The peels also have a soothing effect against skin irritations such as acne and pimples.

Potato peels and potato processing residues can also be converted into lactic acid, which can be used in the production of various cleaning and cosmetic products. Alternatively, the raw material can be used as fuel and can also be converted into methanol [42]. Potato peels can also be used in the pharmaceutical industry; it has a soothing effect against burns and inflammations and also provides moisture to the skin. It also has antibacterial properties. It is also possible to extract many other substances for medicinal use. For example, chlorogenic acid, which is found in both potato tubers and potato peels, has many health benefits. It has an antimicrobial effect, meaning it prevents the proliferation of microbes, kills microorganisms and helps with bacterial infections.

It also reduces the formation of the stress hormone cortisol, which increases blood pressure when taken in excess and can lead to heart disease, obesity, sleep disorders and difficulty concentrating [43].

In addition to being used in cleaning products or cosmetics, potato peels can also be used as fuel and fuel for stoves and fireplaces due to their very slow burning and relatively long durability. If we turn the remaining material into a recyclable material, a circular economy can be created where raw materials are reused instead of wasted. In the future, alternative uses for processing valuable raw materials need to be found. Although it is preferable to offer them for human consumption, they should also be transferred to different industries (Figure 3).

Recently, new trending products have been created from potato peels in different industries.

It has developed sustainable disposable tableware made from potato peel waste [44].

Chip[s] Labs in London has created a bioplastic called Parblex® made from potato peel waste that is compatible with injection molding and 3D printing. This bioplastic has been used in Cubbits London eyewear, Isabel Fletcher clothing buttons and furniture design [45]. Great Wrap is an Australian biomaterials company that has commercialized a 100% home compostable stretch film made by combining starch from potato peels with other organic ingredients[46].

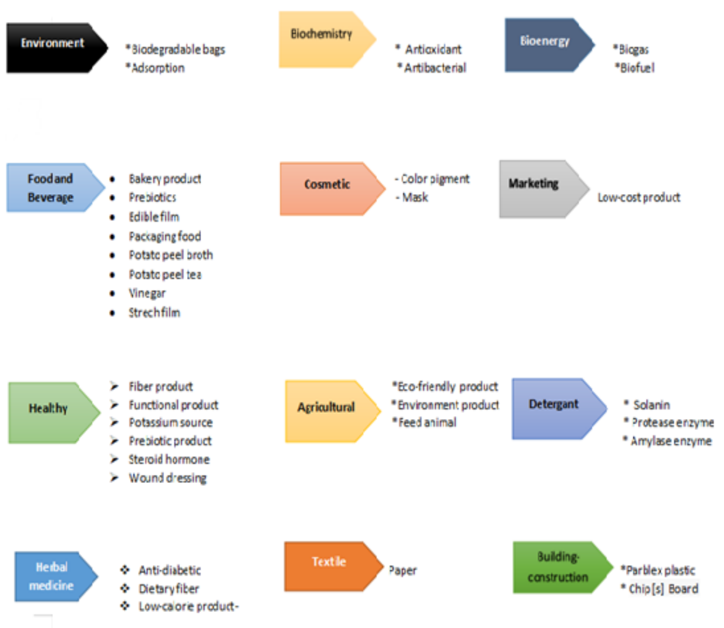

Figure 3. Application of potato peel in different industries.

8. CONCLUSION

Potato peels, which are considered as standard management waste are a valuable deposit of radioactive data, especially phenolic displays with strong antioxidant, antimicrobial and anti-inflammatory characteristics. Since the chemical compound of potato peel includes a rich polyphenol, dietary fibre, vitamin and mineral spectrum, it is a potential ingredient for various diverse applications in the food and non-food industries.

In the food industry, potato peel meal can be used as a natural antioxidant, preservative and functional ingredient, increasing the nutritional profile and shelf life of food products. It can also be included in bakery products, drinks and dietary supplements.

Above and beyond food application, potato peel flour has considerable potential as an important interdisciplinary product in a variety of industries, including pharmaceuticals, cosmetics, bioplastics and animal feed. Moreover, its role in wastewater purification and biofuel production emphasises its contribution to sustainable industry applications. Generally, the valorization of potato peel is in line with the principles of circular economy and sustainability and offers an efficient way to reduce food waste while contributing to various industries. Greater research and technological advances will enhance its practical utility, unlocking its full potential as a valuable bio-resource for multidisciplinary industrial utilisation.

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VALORIZATION OF WASTES AND BYPRODUCTS OBTAINED FROM CRUCIFEROUS VEGETABLES: AN OVERVIEW

Şakir Selçuk SEÇİLMİŞ[1]

1. INTRODUCTION

Cruciferous vegetables, part of the *Brassicaceae* family, are widely recognized for their exceptional nutritional value and health-promoting properties. These vegetables include broccoli, cabbage, cauliflower, kale, Brussels sprouts, radishes, and turnips, among others. These vegetables are rich in vitamins, minerals, fiber, and bioactive compounds, which contribute to human health and have been linked to the prevention of various chronic diseases, including cancer, cardiovascular diseases, and inflammation (Ağagündüz et al., 2022; Favela-González et al., 2020).

However, despite their widespread consumption and the nutritional value they provide, the production of cruciferous vegetables results in significant amounts of waste and byproducts, including stems, leaves, peels, and other parts that are often discarded (Shinali et al., 2024). The disposal of these byproducts presents both an environmental challenge and a missed opportunity for resource recovery. Valorization, the process of transforming waste materials into valuable products, has emerged as a promising approach to minimize

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environmental impacts while promoting sustainability (Berndtsson et al., 2020). In the context of cruciferous vegetables, valorization efforts focus on converting these agricultural byproducts into high-value products such as biofuels, bioplastics, animal feed, and functional food ingredients (Almaraz-Sanches et al., 2022). Additionally, the bioactive compounds found in the byproducts, such as glucosinolates, phenolics, and antioxidants, offer potential for the development of novel functional foods, nutraceuticals, and pharmaceuticals.

Despite increasing awareness of food waste issues and advances in waste recovery technologies, the valorization of cruciferous vegetable by-products remains underutilized and fragmented. Current practices often neglect the significant nutritional and functional potential of these residues, resulting in environmental burden and missed economic opportunities. This chapter aims to present a comprehensive overview of the types, nutritional value, and potential applications of cruciferous vegetable by-products, along with conventional and emerging extraction methods used in their valorization. It focuses on evaluating the technological innovations, postharvest processing strategies, and sustainable utilization approaches that enable the transformation of waste into value-added products, thereby contributing to circular economy objectives.

2. TYPES OF WASTES AND BYPRODUCTS IN CRUCIFEROUS VEGETABLE PRODUCTION

Cruciferous vegetables are widely cultivated and consumed around the world. However, the production of these vegetables generates significant amounts of agricultural waste and byproducts, which, if not properly managed, can contribute to environmental pollution and resource inefficiency (Mago et al., 2022). Cruciferous vegetables, such as cabbage, cauliflower, broccoli, and Brussels sprouts, generate significant amounts of non-edible parts during harvesting and processing. These parts commonly referred to as "byproducts," include outer leaves, thick stems, cores, and damaged or unmarketable portions of the plant (Table 1). These wastes primarily consist of plant materials that are either not harvested or are discarded during processing. Below are the main types of wastes and byproducts generated during cruciferous vegetable production.

Table 1. Common waste and by-products derived from cruciferous vegetables

Vegetables	Main Edible Parts	Common Byproducts
Cabbage	Compact head (leaves)	- Outer leaves (30 40%) - Core - Trimming losses
Cauliflower	White curd (florets)	- Outer leaves - Core/stalk - Short florets or fragments
Broccoli	Florets	- Large leaves (up to 47%) - Stems - Small florets - Field residues
Brussels sprouts	Buds (miniature heads)	- Outer leaves - Stem and stalk - Unmarketable sprouts
Kale	Tender leaves	- Thick stems - Damaged or oversized leaves

2.1. The waste and byproducts types in cruciferous vegetables

2.1.1. Outer leaves

Outer leaves of cruciferous vegetables, such as cabbage, cauliflower, kale, and Brussels sprouts, represent a significant portion of agricultural and post-harvest waste (Chaisamlitpol et al., 2014). These leaves serve as protective outer layers for the plant and are often removed during harvesting, handling, or food preparation due to their tougher texture, larger size, discoloration, or potential exposure to pests and environmental contaminants. Despite being discarded for aesthetic or textural reasons, outer leaves are rich in valuable bioactive compounds, including dietary fiber, vitamin C, chlorophyll, glucosinolates (Tlais et al., 2021), and various phenolic compounds many of which have antioxidant, anti-inflammatory, and anticancer properties. Studies have shown that the outer leaves can contain higher concentrations of certain nutrients compared to the edible cores, indicating their underutilized nutritional potential (Boulismi et al., 2021; Zhao et al., 2020). Their disposal not only contributes to food waste but also represents a missed opportunity for resource recovery. Consequently, there is growing interest in valorizing these leaves through their conversion into animal feed, compost, bioenergy, functional food ingredients, or nutraceutical extracts. However, challenges such as perishability, handling logistics, and consumer acceptance must be addressed to facilitate the sustainable utilization of this nutrient-rich byproduct.

2.1.2. Stems and stalks

The stems and stalks of cruciferous vegetables are often discarded after the edible parts, such as florets and leaves, are harvested (Garcia-Lorca et al., 2025). These parts tend to have a tougher texture and less desirable taste (Hong et al., 2022), making them less popular in the culinary world. For example, the thick stems of broccoli and cauliflower are typically removed and discarded, even though they contain fiber, antioxidants, and other beneficial compounds. The stems of cabbage and kale, though often consumed, are also often left behind or used in small quantities compared to the leaves.

2.1.3. Cores

The cores of cruciferous vegetables, particularly cabbage and cauliflower, constitute a notable portion of post-harvest and processing waste due to their dense, fibrous texture and limited culinary appeal. In cabbage, the core comprising the central white stem that supports the head is typically removed during trimming and preparation, as it is perceived as tough and less palatable compared to the surrounding leaves (Rote et al., 2012). Similarly, in cauliflower, the core includes the central stalk and associated branching stems that anchor the curd. Although these parts are generally discarded, they possess considerable nutritional value, including dietary fiber, calcium, and bioactive compounds such as glucosinolates and polyphenols (Tokuyasu et al., 2022). Studies have demonstrated that the chemical composition of the core, particularly in cabbage, includes antioxidant constituents similar to those found in the outer leaves, albeit in lower concentrations (Cuong et al., 2022). The removal and disposal of cores, which can account for 10–20% of the total vegetable mass depending on variety and processing practices, contribute to the overall biomass loss in the supply chain (Tokuyasu et al., 2022). Therefore, the valorization of these underutilized components, through applications such as dietary fiber enrichment, fermentation substrates, or bio-based materials, represents an emerging opportunity within the framework of sustainable food systems and circular bio-economy initiatives.

3. NUTRITIONAL PROPERTIES OF CRUCIFEROUS VEGETABLES AND THE EFFECT ON HEALTH

Cruciferous vegetables are well known for their remarkable nutritional density and health-promoting bioactive compounds. Their edible parts are characterized by low caloric content and high concentrations of dietary fiber, essential vitamins (notably C, K, and folate), minerals (such as potassium and calcium), and glucosinolates sulfur containing compounds with demonstrated anticancer and antioxidant activities (Podsedek, 2007). For instance, broccoli alone can supply more than 100% of the recommended daily intake of vitamin C per serving (Pennington and Fisher, 2009). In addition to their micronutrient richness, cruciferous vegetables are unique for their content of glucosinolates, sulfur-containing compounds that are converted during chewing and cooking into biologically active substances such as isothiocyanates (e.g., sulforaphane) and indoles (e.g., indole-3-carbinol) (Herr and Büchler, 2010). The nutritional profile for some important cruciferous vegetables is summarized in Table2.

These metabolites have been extensively studied for their potential anticancer, anti-inflammatory, and antioxidant effects (Traka and Mithen, 2009). Moreover, these vegetables are rich in flavonoids and phenolic compounds, contributing significantly to their antioxidant capacity (Verkerk et al., 2009). It is important to note that nutrient composition and phytochemical content can be influenced by factors such as vegetable variety, soil quality, agricultural practices, and cooking methods where methods like steaming tend to preserve more nutrients compared to boiling (Jeffery et al., 2003). Regular consumption of cruciferous vegetables has been associated with a reduced risk of cardiovascular diseases, certain types of cancers (particularly lung, colorectal, and breast cancers), enhanced detoxification processes, and improved metabolic health (Beecher, 1994).

However, during harvesting, processing, and consumption, substantial portions of these vegetables particularly stems, outer leaves, and greens are often discarded as waste. Recent research has revealed that these by-products are not nutritionally inferior; on the contrary, they often contain comparable or even higher levels of fibers, vitamins, minerals, and phytochemicals compared to the traditionally consumed parts (Martínez-Sánchez et al., 2022; Saxena et al., 2023). For instance, broccoli leaves and cauliflower greens exhibit high concentrations of vitamin C, vitamin K, and glucosinolates, positioning them as potent sources of bioactive compounds. Table 3 presents nutritional profile of waste and byproducts of cruciferous vegetables.

Table 2. Nutritional profile for cruciferous vegetables

Vegetable	Energy (kcal)	Water (g)	Carbohydrates (g)	Protein (g)	Fat (g)	Fiber (g)	Vitamin C (mg)	Vitamin K (µg)	Glucosinolates (µmol/g FW)	Notable Features
Broccoli	34	89.3	6.64	2.82	0.37	2.6	89.2	101.6	~13.4	High in folate and vitamin C
Brussels sprouts	43	86.0	8.95	3.38	0.30	3.8	85.0	195.0	~15.0	Rich in vitamin K and fiber
Cabbage	25	92.2	5.80	1.28	0.10	2.5	36.6	76.0	~13.4	High in flavonoids and iron
Cauliflower	25	92.1	4.97	1.92	0.28	2.0	48.2	15.5	~25.3	High in polyphenols and glucosinolates
Kale	35	89.6	4.42	2.92	1.49	4.1	93.4	565.0	~12.0	Excellent source of vitamin K and antioxidants
Mustard greens	27	90.7	4.67	2.86	0.42	3.2	70.0	257.5	~14.0	Rich in vitamin C and glucosinolates
Turnip	28	91.9	6.43	0.90	0.10	1.8	21.0	138.0	~10.0	Good source of vitamin C
Radish	16	95.3	3.40	0.70	0.10	1.6	14.8	1.3	~9.0	Contains anthocyanins and glucosinolates
Chinese cabbage	12	95.0	2.0	1.5	0.2	1.0	45.0	42.0	~12.6	High in vitamin C and minerals

* **Glucosinolate content** is described qualitatively because absolute amounts vary widely depending on variety, soil, and growing conditions. (Mitra et al., 2022; Wang et al., 2022; Dunlop et al., 2024)

Table 3. Nutritional profile for waste types of cruciferous vegetables

By-product	Calories (kcal)	Carbohydrates (g)	Fiber (g)	Protein (g)	Fat (g)	Vitamin C (mg)	Vitamin K (μg)	Glucosinolates*
Broccoli stems	34	6.0	2.6	2.5	0.3	89.0	102	High
Broccoli leaves	53	11.2	4.7	4.2	0.6	93.2	205	Very High
Cauliflower leaves	35	7.5	3.1	2.9	0.2	52.0	140	High
Cabbage outer leaves	28	6.2	2.8	2.3	0.1	39.8	87	High
Radish leaves	28	5.5	3.7	2.0	0.4	81.0	255	High
Turnip greens (leaves)	32	7.1	3.5	1.5	0.3	60.0	251	High

* **Glucosinolate content** is described qualitatively because absolute amounts vary widely depending on variety, soil, and growing conditions. (Gao et al., 2025; USDA FoodData Central, 2024; Artes-Hermandez et al., 2023; Mishra and Poonia, 2020).

In the context of sustainable nutrition and circular economy strategies, the valorization of cruciferous vegetable by-products offers a promising approach to enhance dietary quality while reducing food waste. Integrating both edible parts and by-products into the food system not only maximizes the nutritional potential of these crops but also supports the development of functional foods and nutraceutical products aimed at promoting human health.

4. UTILIZATION OF WASTE AND BY-PRODUCTS OF CRUCIFEROUS VEGETABLES

The processing conditions of cruciferous vegetable waste significantly influence their potential applications. Various methods can enhance the valorization of byproducts from vegetables like cabbage, broccoli, and cauliflower, which are rich in bioactive compounds such as glucosinolates and isothiocyanates. Understanding these processing conditions is crucial for maximizing the health benefits and commercial value of these waste materials.

4.1. Effect of postharvest applications on by-products

Several critical technologies are employed during the postharvest period to stabilize, extract, and repurpose these materials into functional food ingredients or nutraceuticals. High temperatures can lead to a substantial loss of glucosinolates, which are sensitive to heat. This loss can diminish the health-promoting properties of the vegetables (Lafarga et al., 2018; Baenas et al., 2020). Techniques like high-pressure processing and pulsed electric fields preserve glucosinolate content better than traditional thermal methods (Lafarga et al., 2018). These methods can maintain the bioactive compounds, enhancing their potential applications in food and pharmaceutical. Freeze drying retains more of the original characteristics of the vegetables, while hot-air drying at higher temperatures can enhance antioxidant properties but may reduce bioactive compound levels (Bas-Bellver et al., 2022). The choice of drying method impacts the final product's nutritional value. Factors such as temperature, humidity, and storage atmosphere significantly affect glucosinolate levels. Controlled storage conditions can help maintain these compounds, ensuring the waste remains valuable for further processing (Tang, 2022).

Postharvest technologies for the valorization of cruciferous vegetable byproducts are critical for preserving nutritional integrity, recovering functional bioactive compounds, and promoting waste-to-food strategies. The application of sustainable techniques such as green extraction and advanced formulation enables the transformation of these agro-industrial residues into high value ingredients, thereby supporting the goals of a circular bio-economy. However, while the optimization of processing parameters can significantly improve the efficiency and efficacy of valorization, it is equally important to ensure that such technological interventions align with broader sustainability goals and contribute meaningfully to waste reduction efforts within the food industry.

4.1.1. Important waste valorization techniques

Food waste utilization technologies are essential for transforming waste into valuable resources, thereby mitigating environmental impacts and enhancing economic benefits. These technologies not only enhance the economic value of waste but also contribute to environmental sustainability by reducing waste disposal issues. The following sections outline key technologies involved in food waste utilization. The valorization of cruciferous vegetable waste through bio-refinery approaches, anaerobic digestion, and pyrolysis presents a sustainable solution to agricultural waste management.

Bio-refinery approaches can efficiently convert these wastes into high-value products. For example, glucosinolates present in these vegetables can be processed to produce isothiocyanates, compounds known for their anti-inflammatory and anticancer activities. Such conversions not only enhance the therapeutic applications of these wastes but also contribute to the medicinal and food industries by offering bioactive compounds with potential health benefits (Shinali et al., 2024). Biochemical conversion of cruciferous vegetable waste typically begins with pretreatment and enzymatic hydrolysis of lignocellulosic biomass to release fermentable sugars. These sugars serve as substrates in microbial fermentation processes that yield bioethanol, lactic acid, and other industrially relevant bio-chemicals (Ruiz et al., 2022). For instance, lactic acid, a platform chemical, can be polymerized into polylactic acid, a biodegradable bioplastic. Moreover, microbial bio-transformation can convert specific phytochemicals, such as glucoraphanin, into bioactive compounds like sulforaphane, which has received significant attention due to its antioxidant and anticancer properties (Dmytriv et al., 2025; Zhang et al., 2020).

Anaerobic digestion is another viable method for the valorization of these agricultural wastes. It involves co-digestion with other organic wastes like food waste, which can alleviate common issues such as volatile fatty acid accumulation and low buffer capacity. Research indicates that mixing cabbage and cauliflower wastes with food waste at a C/N ratio of 45 yields promising results, including a high biodegradability rate (98%) and a methane yield of approximately 475 mL STP CH_4/g VS. This approach not only adds value to agricultural waste but also mitigates typical anaerobic digestion issues like volatile fatty acid accumulation (Beniche et al., 2020). Through anaerobic digestion, the transformation of cruciferous vegetable waste into energy sources and valuable byproducts highlights its role in promoting circular economy practices and improving environmental sustainability. This application demonstrates a practical method for converting agricultural waste into renewable energy while minimizing the ecological impact of waste disposal.

Pyrolysis is a thermal conversion process that can be applied to cruciferous vegetable waste. It involves the degradation of organic material at high temperatures in the absence of oxygen, resulting in the production of bio-oil, biochar, and syngas. This method of valorization converts agricultural waste into useful byproducts that can be used as renewable energy sources, fertilizers, or soil conditioners, thereby enhancing the sustainability of agricultural practices (Shinali et al., 2024).

Overall, the integration of bio-refinery, anaerobic digestion, and pyrolysis for the valorization of cruciferous vegetable waste provides a comprehensive approach to reducing environmental impact while simultaneously offering economic benefits through the production of value-added products. This multi-faceted approach holds significant promise for enhancing sustainability in agricultural waste management.

4.2. The sustainable utilization of crucifier vegetable by-products

The sustainable utilization of cruciferous vegetable by-products holds significant promise for various industries, including food, pharmaceuticals, and nutraceuticals. These residues are rich in bioactive compounds such as glucosinolates, flavonoids, anthocyanins, carotenoids, and tocopherols—molecules widely recognized for their health-promoting properties. Among these, sulforaphane, a metabolite derived from glucosinolates in broccoli, has shown potential for regulating immune responses in inflammatory conditions (Sim et al., 2023). In the medical field, these by-products can serve as raw materials for the development of value-added therapeutic compounds. Isothiocyanates extracted from cabbage, broccoli, and cauliflower residues modulate cellular signaling pathways and show promise in disease prevention, particularly in oxidative stress and inflammation-related conditions (Shinali et al., 2024).

Moreover, glucosinolate derivatives such as isothiocyanates and indole-3-carbinol demonstrate strong antimicrobial and antifungal activities, making them attractive candidates for functional and therapeutic applications (Favela-González et al., 2020; Sharma et al., 2023). Indole-3-carbinol, for instance, influences pathways relevant to cell proliferation and detoxification (Katz et al., 2018). Fermentation processes can further enhance the value of these by-products. For example, curly kale juice obtained from waste material has shown increased antimicrobial properties during fermentation. Such products offer promising potential in the functional food sector due to their enriched antioxidant capacity and improved microbial safety (Szutowska et al., 2020).

The integration of cruciferous vegetable by-products into food and health systems not only contributes to waste reduction but also promotes a circular bio-economy. Their phytochemical diversity supports the development of functional food ingredients and therapeutic agents targeting chronic conditions such as inflammation, microbial infections, and metabolic disorders.

5. EXTRACTION METHODS OF VALUABLE COMPONENT FROM CRUCIFEROUS VEGETABLES WASTE

The recovery of valuable bioactive compounds from cruciferous vegetable waste presents a promising avenue for valorization; however, these compounds are typically embedded within complex cellular matrices and are often bound to macromolecules such as proteins, polysaccharides, or cell wall components. As a result, the application of efficient extraction techniques is critical to liberate and isolate these bioactive compounds in a usable form. The valorization of cruciferous vegetable waste and byproducts involves various extraction methods that aim to recover valuable nutritional and bioactive compounds. Effective extraction not only enhances the bioavailability, stability, and functional efficacy of the compounds but also facilitates their application in diverse sectors such as food, nutraceuticals, cosmetics, and pharmaceuticals. These methods are crucial for transforming waste into high-value products, thereby contributing to sustainability and economic benefits.

The extraction methods employed for bioactive compounds from cruciferous vegetable waste significantly influence both the yield and quality of the extracted materials. Various techniques, including soxhlet extraction, ultrasound-assisted extraction, microwave-assisted extraction, and supercritical fluid extraction, have been shown to vary in efficiency and effectiveness in recovering valuable phytochemicals. In recent years, green extraction methods such as deep eutectic solvent are very popular. The following subsections detail the current extraction methods and their effects on the nutritional and bioactive compounds present in cruciferous vegetable waste.

5.1. Conventional extraction applications

The selection of an appropriate extraction method is critical for maximizing the recovery of bioactive compounds from plant-based materials, particularly in the context of food waste valorization. Among the commonly used techniques, maceration, Soxhlet extraction, and other solvent-based methods differ significantly in terms of efficiency, temperature requirements, equipment complexity, and suitability for thermolabile compounds. Maceration is one of the simplest and most traditional solid–liquid extraction methods, used to isolate bioactive compounds from plant materials. It involves soaking plant matter in a solvent at ambient or controlled temperatures for a specific period to dissolve and extract the desired phytochemicals. Maceration is based on the diffusion of soluble compounds from a solid matrix into the solvent. The solvent penetrates the plant cells, dissolves intracellular compounds, and allows them to diffuse into the surrounding liquid. In a study by Rodríguez García and Raghavan (2022), maceration using 80%

(v/v) methanol for 24 hours at room temperature was applied to different parts of broccoli. Among the samples, broccoli leaves exhibited the highest total phenolic content, reaching 1714.011 ± 1.223 μg GAE/g, followed by florets (347.228 ± 0.956 μg GAE/g) and stems (224.174 ± 0.922 μg GAE/g). These findings underscore the potential of broccoli leaves typically considered agricultural waste as a valuable source of phenolic compounds when extracted through a simple maceration process. Soxhlet extraction is a conventional solid–liquid extraction method commonly used to recover thermally stable bioactive compounds from plant matrices. It operates by continuously cycling heated solvent through a sample over several hours, enabling exhaustive extraction of target compounds. Soxhlet extraction remains widely utilized in the preliminary valorization of agro-industrial vegetable waste, including that from Brassicaceae species. In the study conducted by Zafar et al. (2024), ethanol extracts of red cabbage were obtained using the Soxhlet extraction technique with 1, 2, 4, and 8 extraction cycles. Among the tested conditions, the extract obtained after 4 Soxhlet cycles demonstrated the highest total phenolic content, total flavonoid content, as well as the strongest DPPH free-radical scavenging and reducing power activities.

Solvent extraction is a widely used classical technique for the recovery of bioactive compounds from plant-based waste materials. The method relies on dissolving target compounds present in the plant matrix into a suitable solvent, thereby transferring them into the liquid phase. The efficiency of solvent extraction is influenced by several factors, including the polarity of the solvent, extraction time, temperature, solvent-to-solid ratio, and the particle size of the plant material. Commonly used solvents include water, ethanol, methanol, acetone, and hexane, with ethanol–water mixtures often preferred due to their safety and suitability for food and pharmaceutical applications.

Extraction is typically conducted under controlled temperature conditions with agitation, followed by filtration and solvent removal (e.g., via rotary evaporation) to obtain concentrated extracts. In a study by Sasaki et al. (2012), solvent extraction using 0.1 % formic acid in 80 % v/v methanol at room temperature was applied to broccoli leaves from six cultivars. The results indicated that soxhlet enabled glucoraphanin recovery from 12.2 to 119.4 (mg/100 g fresh leaves). Núñez-Gómez et al. (2022) evaluated the total fiber fraction and insoluble fiber fraction potential of broccoli stalks. Extraction with aqueous ethanol (80%) and water yielded total fiber ratio of 67% and 70%, respectively.

5.2. Non-conventional extraction methods

Non-conventional or emerging extraction techniques have been developed to address the limitations of traditional methods such as maceration, Soxhlet extraction, and conventional solvent extraction. These innovative approaches aim to enhance extraction efficiency, reduce solvent consumption, minimize processing time, and better preserve thermolabile bioactive compounds. Among the most widely applied non-conventional techniques are ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), and enzyme-assisted extraction (EAE). In addition to these methods, the use of Natural deep eutectic solvents (NADES) has emerged as a green and sustainable alternative to conventional organic solvents.

5.3.1. Ultrasound-assisted extraction

Ultrasound-Assisted Extraction (UAE) is a widely used non-conventional technique that utilizes high-frequency ultrasonic waves (typically 20–100 kHz) to enhance the extraction of bioactive compounds from plant materials. It is considered a green, efficient, and scalable method, especially suitable for heat-sensitive compounds and valorization of agro-food waste. In a study optimizing UAE of broccoli leaf and floret by-products, distilled water was used as the solvent and various parameters (solid/liquid ratio, temperature, and time) were tested. Results showed that TPC was significantly higher in leaves, while florets had greater sulforaphane content. Optimal conditions varied slightly by compound but generally included 25 °C, 2:25 g/mL ratio, and 15–20 min extraction time. Tissue type and solid/liquid ratio had a significant impact, with lower energy conditions being more efficient (Martinez-Zamora et al., 2024). Gonzales et al. (2014) reported that non-extractable phenolics (NEPs) in cauliflower waste were more abundant than extractable phenolics, underscoring their potential in waste valorization. The highest NEP yield (7.3 ± 0.17 mg GAE/g dry weight) was obtained through alkaline hydrolysis combined with sonication (2 M NaOH, 60 °C, 30 min), outperforming conventional extraction methods.

5.3.2. Microwave-assisted extraction

Microwave-Assisted Extraction (MAE) is a non-conventional and green extraction technique that uses microwave energy to rapidly heat the solvent and plant matrix, enhancing the extraction of bioactive compounds. The technique relies on the interaction between microwave radiation (typically 2450 MHz) and polar molecules, resulting in internal heating, cell wall rupture, and improved mass transfer. This leads to higher extraction yields in significantly reduced time compared to traditional methods. Rodríguez-García & Raghavan (2022) found that MAE resulted in efficient extraction of TPC and sulforaphane from broccoli by-products under optimized conditions, with leaves showing the highest phenolic yield. Sookjitsumran et al. (2016) compared MAE and preheated solvent extraction using outer cabbage leaves. MAE (0.37 W/g for 9 min) matched or exceeded phenolic and glucosinolate yields of conventional method and required less energy.

5.3.3. Supercritical Fluid Extraction

Supercritical Fluid Extraction (SFE) is a non-conventional, eco-friendly extraction technique that utilizes fluids at temperatures and pressures above their critical points to extract bioactive compounds from plant materials. The most commonly used fluid in SFE is supercritical carbon dioxide (SC-CO_2), which exhibits gas-like diffusivity and liquid-like solvating power, allowing it to efficiently penetrate the plant matrix and dissolve target compounds. Supercritical fluid extraction (SFE) was used to isolate lipids from broccoli leaves, optimizing parameters at 60 °C, 300 bar, and 3 mL/min. GC-MS analysis showed that SFE yielded a higher proportion of unsaturated fatty acids, particularly α-linolenic acid (18:3 n−3), compared to Soxhlet extraction using hexane and chloroform/methanol (Arnaiz et al., 2010).

5.3.4. Enzyme-assisted extraction

Enzyme-Assisted Extraction (EAE) is a green and selective technique that utilizes cell wall-degrading enzymes such as cellulases, pectinases, hemicellulases, or proteases to disrupt plant tissue structures, thereby enhancing the release and solubilization of intracellular bioactive compounds. This technique is particularly effective for extracting polyphenols, glucosinolates, flavonoids, and proteins from cruciferous vegetable wastes. In addition to being an effective standalone method, EAE is widely applied as a pre-treatment to improve the efficiency of subsequent extraction techniques, including UAE, MAE, and SFE. By breaking down the structural barriers of plant cell walls, enzymes increase solvent penetration and facilitate mass transfer, leading to significantly higher yields, shorter extraction times, and better preservation of bio-actives when used in combination with other methods. Enzymatic pretreatment using commercial cellulolytic and pectolytic enzymes at varying enzyme-to-substrate ratios (0.2–4.8%) significantly enhanced protein recovery from cauliflower and broccoli leaves. The highest yields were observed at the 4.8% ratio, indicating a clear dose response relationship between enzyme concentration and extraction efficiency.

5.3.5. Natural deep eutectic solvent extraction

NADES are bio-degradable; low-toxicity solvent systems composed of natural compounds such as sugars, amino acids, and organic acids, and are particularly suitable for the extraction of polar bioactive compounds like phenolics and glucosinolates. These solvents are often employed in combination with physical extraction techniques such as UAE and MAE to enhance selectivity and yield. Collectively, these non-conventional approaches are increasingly utilized in the valorization of agro-industrial wastes, including cruciferous vegetable by-products, due to their environmental and functional advantages. Cruciferous vegetable waste yields several value-added products when processed with natural deep eutectic solvents. Broccoli residues provide phenolic acidsneochlorogenic, ferulic, erucic, quinic, chlorogenic, and caffeic acids at a yield of 4.91 mg/g; these compounds exhibit both antioxidant and antimicrobial properties (Cao et al., 2023). Broccoli extracts using choline chloride and betaine systems yield Flavonoid quercetin, isorhamnetin, and kaempferol with recoveries ranging from 88.45% to 99.01% (Dai and Row, 2019). These reports support the potential of cruciferous vegetable waste to generate compounds with high antioxidant activity and additional bioactive properties through natural deep eutectic solvent extraction.

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