

Review

Potato Processing Waste as a Reservoir of Bioactive Hydroxycinnamates: A Critical Review

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Abstract: Natural resources are currently overexploited to provide food supply for the ever-increasing world population, and because of the intensification of agricultural and food production, there is a growing rate of waste generation. This waste biomass is usually dumped into landfills, causing unprecedented damage to ecosystems. Nowadays, circular economy strategies are channeled towards waste harnessing, aiming at reducing the irrational use of resources and minimizing waste generation. Potatoes are the second largest food crop after cereals, and there is an overwhelming amount of waste derived from potato tuber processing, composed almost exclusively of peels. Potato peels (PPs) are considered a source of polyphenolic compounds, largely represented by chlorogenic acid and other structurally related hydroxycinnamates, which possess a spectrum of bioactivities; however, there is a lack of analytical data compilations that could be of assistance in pertinent studies. With this as the conceptual basis, the scope of this review focused on a particular class of polyphenols, the so-called hydroxycinnamates, to deliver compiled data associated with the occurrence, retrieval, and application of this group of compounds derived from potato waste with major emphasis being given to PPs. It is believed that the collection of data of this nature, due to their undisputed significance in studies pertaining to bioeconomy, biorefinery, and food waste valorization, would provide a highly useful contribution to the field.

Keywords: bioeconomy; food waste valorization; potato peels; polyphenols; extraction



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1. Introduction

It is now beyond any doubt that activities associated with agricultural production and food processing constitute major contributors to biowaste generation. Waste biomass is generated as a result of agricultural practices, which may include but are not limited to exfoliation, pruning, post-harvest screening, and/or losses, etc. On the other hand, the processing of plant crops for the production of safe and palatable foods inevitably involves the accumulation of rejected parts and tissues, such as leaves, roots, peels, seeds, stems, etc. Thus, an outstanding number of side streams originate from the so-called agri-food sector, which is emerging as an environmental issue of paramount importance [1,2].

The environmental risks related to these biowastes stem mainly from the composition of the rejected materials, which are rich in moisture, thus making them prone to enzyme/microbial spoilage, but also bear a very high organic load. This load is principally attributed to the multitude of organic compounds that largely occur in plant material, including proteins, lipids, carbohydrates, and a wide spectrum of secondary metabolites, such as essential oils, pigments, and polyphenols. This load makes most agri-food residues particularly recalcitrant materials, and therefore, dumping plant food waste in landfills or releasing it uncontrollably into the environment (i.e., rivers, lakes, sea) may cause severe

pollution and entail dire consequences to the global eco-system, public health, and human and animal well-being [3,4].

On the other hand, owing to the richness and bewildering diversity of phytochemicals, biowastes from the agri-food sector are now regarded as a vast pool of substances with high added value [5]. This is because several classes of these phytomolecules possess significant bioactivities, such as antioxidant, anti-inflammatory, and anti-microbial activities, but also cardioprotective, neuroprotective, and chemoprotective properties [6,7]. Thus, harnessing agri-food biowastes within a biorefinery framework to recover high-added-value bioactive chemicals has emerged as a prospect with enormous potential, wide applicability, and high profitability. The potential of exploiting such compounds spreads over various industrial activities, such as the manufacture of functional foods and nutraceuticals, cosmetics with natural bioactive ingredients, and pharmaceutical formulations [8–12].

Over the last fifteen years, there has been an overwhelming expansion in research pertaining to the development of technologies that would enable the efficient recovery of a range of biologically important phytochemicals from residual sources. Special attention has largely been given to polyphenols, which are probably the most prominent class of secondary metabolites that occur widely in agri-food wastes, and which encompass several subclasses and a vast range of structures. Polyphenols have been a subject of intense examination, owing to (i) their particularly high load in many side streams, (ii) their bewildering diversity of form, and (iii) their well-documented biological properties [13,14].

2. Agri-Food Wastes as Sources of Precious Bioactive Polyphenols—The Case of Potato Processing Residues

Potatoes (*Solanum tuberosum*) are a crop widely grown in many areas around the globe that represents a staple for roughly 1.3 billion people, with recent estimations giving a world production volume of over 376 million tons in 2021 [15]. Potatoes are tubers consumed by large populations, and after cereals, they are considered the most important food crop. Potatoes are regularly processed on an industrial scale for the manufacturing of several commodities, such as chips, puree, and French fries, and as a consequence, the potato processing industry is responsible for the generation of waste streams attributed primarily to tuber peels, which account for 15 to 40% of the initial fresh weight [16]. Based on the total amount of potato that undergoes processing, this percentage can be translated into about 70 and 140 thousand tons of potato peels (PPs) worldwide on an annual basis.

PPs represent by far the principal potato processing residue, and due to their composition and abundance, they have been extensively examined as a valuable feed for biorefinery processes and particularly the production of polyphenol-enriched extracts. The major polyphenol occurring in PPs is chlorogenic acid (*trans*-5-*O*-caffeoyl quinic acid), which is frequently accompanied by some isomers (i.e., neochlorogenic acid), and non-conjugated hydroxycinnamates, such as caffeic and ferulic acids [17,18]. Such compounds are regarded as principal PP bioactives, and a range of properties have been associated with their activities. Moreover, PP extracts have been successfully assayed as natural food antioxidants and effective replacers of synthetic ones [19]. Thus, a plethora of processes have been developed for the production of polyphenol-enriched extracts, based on both conventional and emerging technologies [18,20].

The scope of this review focused on a particular class of polyphenols, the so-called hydroxycinnamates, on the ground of the realization that there was a lack of compiled data associated with the occurrence, retrieval, and application of this group of compounds derived from potato wastes, with major emphasis being given to PPs. The compilation of data of this nature, due to their undisputed significance in studies pertaining to bioeconomy, biorefinery, and food waste valorization, would make a highly useful contribution to the

field. With this as the conceptual basis, the study was carried out via a systematic search, performed in the databases Web of Science, Scopus, and Google Scholar (1993–2024) in October 2024 using the following search terms: (hydroxycinnamates OR phenolic acids OR chlorogenic acids) AND (potato peels OR potato wastes OR potato by-products OR potato processing residues OR bioactivity OR properties).

Studies were only included if they considered the occurrence, extraction, biotransformation, and other practical applications of compounds derived from potato wastes/by-products/residues, as well as general information on the chemical and biological properties of hydroxycinnamates. Studies associated with potato tuber composition, specific medical applications of potato peel extracts, molecular biology and biotechnology, and the chemical synthesis of hydroxycinnamates were excluded. Studies on total polyphenol extraction and determination in potato wastes that did not report specific information on hydroxycinnamates were excluded. Using these filters, over 130 articles were screened via the title/abstract/full text, and finally, 86 articles were included in the review.

3. Hydroxycinnamate Phytochemicals—Properties and Bioactivities

The main structural feature of a phenolic acid is a single aromatic ring, while hydroxycinnamic acids (e.g., ferulic, caffeic, *p*-coumaric, and sinapic acids) bear a side chain of a 2-propenoic acid group [21]. Further structure diversification may derive from the number and spacial arrangement of phenolic hydroxyl groups and/or further substituents on the aromatic ring. Among the most common and well-known HCAs are *p*-coumaric acid, caffeic acid, ferulic acid, and sinapic acid, and some typical, major hydroxycinnamates (HCAs) are depicted in Figure 1. Hydroxycinnamates or phenylpropanoids (C6–C3 compounds) are secondary plant metabolites, and their biosynthesis in plants occurs through the shikimate and phenylpropanoid pathways [22]. They are important compounds, as they are precursors for the biosynthesis of many other polyphenolic metabolites, and may be encountered in numerous plant tissues, such as cereals, fruits, legumes, nuts, and oils, and their by-products.

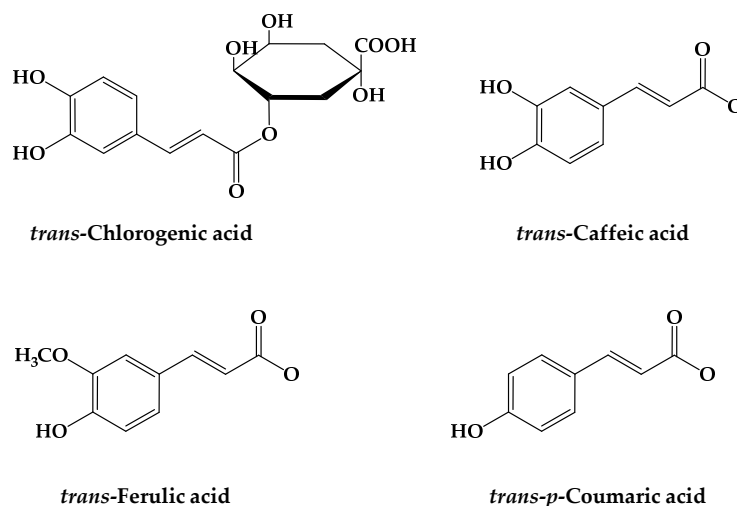


Figure 1. Some major hydroxycinnamates that are frequently encountered in plant foods and their processing residues.

HCAs may occur less frequently as free carboxylic acids, whereas conjugates including esters formed with hydroxylic acids such as quinic and tartaric acid, or carbohydrates, are of significantly higher abundance [23]. HCAs may also be found as amides, formed through the combination of the parent molecule with an amino acid or an amine. HCAs such as ferulic acid, *p*-coumaric acid, and sinapic acid may be found ester-linked to plant cell wall

polymers, acting as cross-linking agents between polysaccharide chains or between proteins and lignin. Ferulate derivatives are quantitatively the most important cross-links in the plant cell wall. Radical and/or light-induced coupling reactions in several plant tissues may lead to the formation of HCA dimers and, in case of radically induced reactions, to oligomers (trimers and tetramers). HCAs and their derivatives can also cross-couple with monolignols, and they can be incorporated as co-polymers into lignins [24].

Chlorogenic acid (5-*O*-caffeoylquinic acid) is composed of caffeic acid esterified with quinic acid, and it is probably the most abundant HCA derivative. Along with several of its isomers, it occurs in a number of plant tissues, such as fruits, vegetables, and herbs, as well as in coffee [25]. However, chlorogenates are considered a wide family of structurally related compounds that include mono-esters of *p*-coumaric and ferulic acid with quinic acid (termed as *p*-coumaroylquinic acid-pCoQAs and feruloylquinic acid-FQAs, respectively), as well as di-esters, tri-esters, the single tetra-ester of caffeic acid, mixed di-esters of caffeic and ferulic acid or caffeic and sinapic acid, and mixed esters involving various derivatives of one or three caffeic acid residues with aliphatic acid residues, such as glutaric, oxalic, and succinic acids [26].

By virtue of the plethora of their bioactivities, HCAs are regarded as natural substances of high nutritional significance, primarily as abundant dietary antioxidants. The antioxidant properties of major HCAs have been well-documented, and several reports on structure–activity relationships are available in the literature [22,27,28]. Nevertheless, the biological interest of HCAs goes far beyond their antioxidant behavior, since they have been found to be implicated in various biochemical events related to a spectrum of disorders/diseases, with beneficial influence on human health [23,29–31].

For ferulic acid, one of the most frequently encountered HCAs, a spectrum of pharmacological activities have been described, including cholesterol-lowering effects, preventive action against thrombosis and atherosclerosis, antimicrobial and anti-inflammatory activity, and cancer chemopreventing properties [32]; involvement in Alzheimer’s disease, cardiovascular disorders, and diabetes [33]; and the expression of antimutagenic and anti-hypertensive effects [21]. Likewise, chlorogenic acid (CGA) and other widespread chlorogenate derivatives have been implicated in several advantageous health properties, such as hepatoprotective activities; antioxidant, antiviral, and antibacterial effects; anti-cancer and anti-inflammatory properties; reductions in the risk of cardiovascular disease; and reductions in the relative risk of diabetes and Alzheimer’s disease [26]. Furthermore, chlorogenates may exert hypoglycemic activity, antiobesity effects, and gastrointestinal flora regulation [34,35].

4. Hydroxycinnamate Recovery from Potato Processing Side Streams—A Critical Appraisal

4.1. Conventional Technologies

Undisputedly, common conventional extraction methodologies for effective HCA recovery from PPs are frequently used as simple and straight-forward means. As can be seen in Table 1, thirteen works on polyphenol extraction from PPs were published between 1993 and 2024, reporting on the hydroxycinnamate composition of extracts generated from PPs, using techniques involving solvent extraction and settings pertaining to residence time, temperature, and stirring regime [36–48]. The most frequently used solvent is ethanol (EtOH), which is relatively cheap, produced from renewable sources, possesses good solvation properties for PP polyphenols, and is non-toxic. In most cases, EtOH is used in combination with water, with proportions varying from 29 [45] to 95% [36]. However, the most reliable data are those derived from optimization assays and not those employed empirically or arbitrarily.

Table 1. Conventional extraction methods implemented for the recovery of HCAs from potato processing residues.

Residue	Solvent	Residence Time (min)	Temperature (°C)	Stirring Speed (rpm)	Liquid-to-Solid Ratio (mL g ^{−1})	Yield/Total Polyphenols (mg g ^{−1} DM)	Yield/HCAs (mg g ^{−1} DM)	Reference
Defatted PPs	95% EtOH	60 × 3	Ambient	N.r. *	5 × 3	N.r.	Caffeic acid: 2.78–2.96 Chlorogenic acid: 7.53–8.21 <i>p</i> -Coumaric acid: 0.42–0.46 Ferulic acid: 1.74–1.92	[36]
PPs	Water	30	100	N.a. **	5.8	N.r.	Chlorogenic acid: 0.30 Caffeic acid: 0.014	[37]
PPs	Absolute EtOH	N.a.	Ambient	N.a.	6	0.71 CTE	Chlorogenic acid: 0.276	[38]
PPs	80% EtOH	N.a.	Ambient	N.a	10	4.9 FAE	Chlorogenic acid: 2.39 Caffeic acid: 0.54	[39]
PPs	MeOH/water (8/2)	N.r.	Ambient	N.r.	N.r.	2.2–4.3	Caffeic acid: 0.21–0.50 Chlorogenic acid: 0.98–2.83 <i>p</i> -Coumaric acid: 0–0.09 Ferulic acid: 0.02–0.09	[40]
PPs	MeOH	30	75 °C	N.r.	50	1.5–3.3 GAE	Chlorogenic acid: 0.78–2.79 Caffeic acid: 0.26–0.72	[41]
PPs	MeOH/water/acetic acid (80:19.5:0.5)	30	4 °C	1000	15	1.5–10.7 GAE	Caffeic acid: 0.03–0.42 Chlorogenic acid: 0.32–21.93 Neochlorogenic acid: 0.18–0.25 Cryptochlorogenic acid: 0.23–1.68 <i>p</i> -Coumaric acid: 0–0.02 Ferulic acid: 0–0.14	[42]
PPs	70% acetone	60	Ambient	500	15		Caffeic acid: 0–0.039 Chlorogenic acid: 0.05–0.497	[43]
PPs	EtOH/acetic acid 95/5	4320	Ambient	N.r.	10	14 GAE	Caffeic acid: 3.33 Chlorogenic acid: 3.46 Ferulic acid: 0.03	[44]
PPs	Water	4320	Ambient	N.r.	15	4.2 GAE	Caffeic acid: 0.57 Chlorogenic acid: 1.60 Ferulic acid: -	[44]
PPs	29–36% EtOH	150	Ambient	200–800	50–90	10.31 CGAE	Chlorogenic acid: 0.21–0.25 Caffeic acid: 0.06–0.07	[45]
PPs	40% 1-propanol	60	90 °C	500	10	19.3 CGAE	Caffeic acid: 0.77 Chlorogenic acid: 1.77 <i>p</i> -Coumaric acid: 0.02	[46]
PPs	50% EtOH	120	Ambient	100	25	48.9 GAE	Caffeic acid: 1.27 Chlorogenic acid: 0.29	[47]
PPs	Water	70	90 °C	N.a.	10	3.5	Caffeic acid: 0.119 Chlorogenic acid: 0.005 <i>p</i> -Coumaric acid: 0.026	[48]

* Not reported; ** not applicable.

On the other hand, alternative solvents including water, methanol (MeOH) [41], and 1-propanol/1.5% sulfuric acid [46] have also been used. In the latter case, the presence of sulfuric acid has been shown to be pivotal in attaining significantly increased yields. This parameter has never been investigated before, and it would merit more profound attention to clarify the role of solvent acidification in maximizing PP polyphenol extraction. Such an approach would be of value in light of other recent studies that have demonstrated the importance of sulfuric acid in achieving increased chlorogenate recovery from coffee silverskin [49].

Residence time varies from 30 min up to 72 h. In this case too, optimization and/or kinetics could indicate optimum settings to avoid unnecessary extension of the extraction period. Similarly, in most cases, ambient temperature is preferred over heating, yet in an extraction process, using the optimal temperature setting may be critical to both increasing yield and protecting labile compounds from decomposition [50]. This also holds true for the stirring speed, which is not reported in several instances. However, as proven by some studies [45], optimization of stirring might be crucial in maximizing extraction yield from PPs.

The liquid-to-solid ratio usually employed to carry out the extractions varies from 5 to 90 mL g⁻¹. In the studies considered, no consistent pattern can be detected regarding the correlation between this setting and the HCA yield, yet it is irrefutable that regulation of the ratio between the solid material and the volume of the solvent could be of paramount importance to the whole process. This is because excessive solvent volume may result in redundant solvent use and an increase in the associated cost, as well as imposing time-consuming steps for solvent removal/recovery. Furthermore, the extracts obtained when a relatively high liquid-to-solid ratio is chosen may be quite dilute, which would pose obstacles for practical applications if non-volatile solvents are used. On the other hand, the ratio between the solid material and the solvent cannot drop below a certain level, as this could lead to insufficient mixing and reduced entrainment of the solute into the liquid phase [50]. Therefore, optimizing the proportion between the amount of dry PP and the amount of solvent is another factor that has been poorly studied and merits further investigation.

The total polyphenol yield varies from 1.5 to as high as almost 49 mg per g of dry PP weight, usually expressed as gallic acid equivalents (GAE) or chlorogenic acid equivalents (CGAE) using the Folin–Ciocalteu assay. Such large differences reflect the varying potencies of the extraction methodologies implemented, but they could also be largely ascribed to varietal (genetic) variations in the polyphenolic load and composition [51]. This argument could be supported by previous examinations on PPs obtained from different potato varieties, where total polyphenol yield ranged from 1.5 to 3.3 mg GAE g⁻¹ DM [41] and from 1.5 to 10.7 mg GAE g⁻¹ DM [42]. In the latter study, PPs originating from the purple-fleshed Vitelotte variety were the richest. Additionally, it should also be underlined that, since the major phenolics occurring in PPs are CGA and caffeic acid, it would be advisable to use either standard for constructing calibration curves to obtain more-accurate estimations for total polyphenol yield. Results expressed in gallic acid, CGA, or caffeic acid equivalents may not be comparable, and this complicates critical assessment of the literature data.

The yield of individual HCAs also displays large variations, but it is clearly showcased that the predominant metabolite in PPs is CGA, whose content may range from 0.21 [45] to 21.93 [42] mg g⁻¹ DM. CGA is accompanied by caffeic acid, which appears to be the second-most abundant HCA, with its content varying from 0.07 [45] to 3.33 mg g⁻¹ DM [44]. Other HCAs, i.e., *p*-coumaric and ferulic acid, and some derivatives (amides) are less frequently reported, while their content does not exceed 1.92 mg g⁻¹ DM.

4.2. Emerging Technologies

Arguably, ultrasound-assisted extraction (UAE) is the commonest non-conventional methodology applied for the extraction of PP polyphenols, as exemplified by the seven analytical studies reported in the literature between 2013 and 2023 [52–58] (Table 2). However, most of these studies present serious shortcomings, related mainly to the omission of significant parameters of ultrasonication. First, the majority of these examinations were carried out using ultrasonication baths, which provide ambiguous results and cannot be used for scale-up trials. Second, in some cases, variables such as ultrasound intensity are reported based on the nominal power of the device used, but this is highly inaccurate.

The actual ultrasonication power dissipated to the system should always be determined on the basis of calorimetric measurements [59,60].

Aside from these drawbacks, it is worth noting that the evidence that emerged from some examinations suggests UAE to be more effective compared to conventional extraction. For example, it has been shown that the UAE of PPs may yield 2.3 times higher total polyphenols compared to conventional solid–liquid extraction, 1.1 times higher chlorogenic acid levels, and 1.5 times higher caffeic acid levels [55]. In the same study, it was also pointed out that ultrasonication at a frequency of 33 kHz was more effective than that at 42 kHz, highlighting the importance of ultrasonication settings. Other examinations also demonstrated the effectiveness of UAE over conventional maceration in obtaining PP extracts that were more enriched with polyphenols and with stronger antioxidant activity [58]. By contrast, polyphenol extraction from PP pellets was of significantly higher efficacy when performed under heating and stirring compared to ultrasonication [61]. These contradictory findings dictate that comparison among various extraction methodologies requires more profound scrutiny of their performance on a comparative basis.

Another issue that has been tackled regarding the recovery of HCAs from PPs is the case of bound phenolics. Although this was a subject of earlier works [39,40], latter examinations demonstrated that significant amounts of ferulic acid may be liberated upon PP treatment with NaOH, highlighting the higher potential of PP exploitation [52]. However, such a treatment would require previous recovery of free HCAs and/or the addition of protective agents (i.e., ascorbic acid), since compounds such as CGA and caffeic acid, which predominate the fraction of free HCAs in PPs, are prone to oxidation under alkaline conditions. Thus, uncontrolled alkali treatment of PPs would inevitably lead to significant HCA losses [53,62].

In addition to UAE, several other non-conventional techniques have been used to effectively extract HCAs from PPs [63–68], as shown in Table 3. Microwave-assisted extraction, which is a technique that has gained some interest, has been reported on once [63], with rather low yields in total polyphenols and HCAs compared to conventional and UAE methods. This was also the case for the application of subcritical water [64], pulsed electric field pretreatment [66], and infrared-assisted extraction [48]. To the contrary, extraction with a glycerol/ammonium acetate (3/1) deep eutectic solvent was shown to afford 12.04 mg of total hydroxycinnamates and total flavonoids, although the yields of individual HCAs were not determined [65]. Similarly, the use of 0.5 mM aqueous hydroxypropyl β -cyclodextrin as the extracting medium yielded total polyphenol levels over 17 mg CGAE g^{−1} DM, but the yields of CGA, caffeic acid, and ferulic acid were rather moderate [67].

Table 2. UAE extraction methods implemented for the recovery of HCAs from potato processing residues.

Residue	Solvent	Residence Time (min)	Temperature (°C)	Device	Liquid-to-Solid Ratio (mL g ⁻¹)	Yield/Total Polyphenols (mg g ⁻¹ DM)	Yield/HCAs (mg g ⁻¹ DM)	Reference
PPs	Methanol/acetone/water (7/7/6)	20	30 °C	N.r. *	15	0.4–7.2	Caffeic acid: 0.001–0.66 Chlorogenic acid: 0.07–0.31 <i>p</i> -Coumaric acid: 0–0.05 Ferulic acid: 0–0.79	[52]
PPs	Water/EtOH/acetic acid (46/51/3)	30 (maceration) 30 (stirring) 20 (sonication)	Ambient	N.r.	2.5	N.r.	Neochlorogenic acid: 0.13 (fresh weight) Chlorogenic acid: 0.78 Caffeic acid: 0.05	[53]
PPs	59% EtOH 83% glycerol	90	77–80	Ultrasonication bath	81–84	8.7–9.1 CAE	Caffeoylquinic acids: n.d. N-[2-hydroxy-2-(4-hydroxyphenyl)ethyl] ferulamide: n.d	[54]
PPs	80% MeOH	30–900	30–45	Ultrasonication bath	10	7.7 GAE	Chlorogenic acid: 0.26 Caffeic acid: 0.13	[55]
PPs	55% EtOH	35	35 °C	Ultrasonication bath	10	6.4 GAE	1-O-caffeoylquinic acid: 0.35–1.38 Chlorogenic acid: 1.27–4.10 4-O-caffeoylquinic acid: 0.37–1.24 Caffeic acid: 0.16–1.22 Bis(dihydrocaffeoyl)-spermidine: 0.02–0.13 5-O-feruloylquinic acid: 0.02–0.08 Tris(dihydrocaffeoyl)-spermidine: 0.02–0.05 Ferulic acid derivative: 0.05–0.12 N-[2-hydroxy-2-(4-hydroxyphenyl)ethyl] ferulamide: 0.09–0.14 3,4-di-O-caffeoylquinic acid: 0–0.09 3,5-di-O-caffeoylquinic acid: 0.004–0.40 4,5-di-O-caffeoylquinic acid: 0.002–0.16	[56]
PPs	70% EtOH	30	50 °C	Ultrasonication bath	20	1.6–3.6	Caffeic acid: 0.27–0.70 Chlorogenic acid: 0.44–0.91 <i>p</i> -Coumaric acid: 0–0.16 Ferulic acid: 0–0.03	[57]
Potato sprouts	70% EtOH/1.7 mM ascorbic acid	5	Ambient	Sonicator	10	7.9 GAE	3-O-caffeoylquinic acid: 0.15–0.27 4-O-caffeoylquinic acid: 0.06–0.79 Chlorogenic acid: 1.21–4.98 Caffeic acid: 0.04–0.4	[58]

* Not reported.

Table 3. Various emerging extraction methods implemented for the recovery of HCAs from potato processing residues.

Residue	Solvent	Residence Time (min)	Temperature (°C)	Other Settings	Liquid-to-Solid Ratio (mL g ⁻¹)	Yield/Total Polyphenols (mg g ⁻¹ DM)	Yield/HCAs (mg g ⁻¹ DM)	Reference
PPs	67–100% MeOH	15	N.r. *	Microwave power level: 10–15%	20	3.9 GAE	Caffeic acid: 1.33 Chlorogenic acid: 1.35 Ferulic acid: 0.50	[63]
PPs	Subcritical water	60	160–180	Pressure: 6 MPa	4.5	0.46 GAE	Caffeic acid: 0.122 Chlorogenic acid: 0.286 <i>p</i> -Coumaric acid: 0.008 Ferulic acid: 0.015	[64]
PPs	Glycerol/ammonium acetate (3/1) deep eutectic solvent	180	80	Stirring speed: 600 rpm	100	12.04*	Caffeoylquinic acid: n.r Caffeoylspermine: n.r di-Caffeoylquinic acid: n.r	[65]
PPs	52% EtOH	230	50	Pulsed electric field pretreatment	20	1.1 GAE	Caffeic acid: 0.07 Chlorogenic acid: 0.37 <i>p</i> -Coumaric acid: 0.008	[66]
PPs	0.5 mM aqueous hydroxypropyl β -cyclodextrin	150	30	Stirring speed: 800	80	17.3 CGAE	Caffeic acid: 0.89 Chlorogenic acid: 0.84 Neochlorogenic acid: 0.29 Ferulic acid: 0.11	[67]
PPs	Supercritical CO ₂ /MeOH		80	CO ₂ flow: 18 g min ⁻¹ Pressure: 350 bar	N.a. **	5.24 GAE	Caffeic acid: 0.92 Chlorogenic acid: 3.87 Neochlorogenic acid: 0.44 Isochlorogenic acid A: 0.21 Isochlorogenic acid B: 0.33 <i>p</i> -Coumaric acid: traces	[68]
PPs	Water	10	80	Infrared-assisted extraction	10	3.5 GAE	Caffeic acid: n.d Chlorogenic acid: 0.02 <i>p</i> -Coumaric acid: n.d	[48]

* Not reported; ** Not applicable.

5. Applications of Potato Waste Extracts—Selected Topics

5.1. Food Applications

Owing to their antioxidant potency, PP extracts have been tested primarily as food additives for shielding various commodities against oxidative deterioration [69–71], and they have been proposed as candidates for replacing synthetic antioxidants [72]. In lipid foods such as sunflower oil, PP extracts were found to prevent the onset of oxidative rancidity [73], and the addition of PP extracts to yoghurt resulted in increased antioxidant activity [74]. PP constituents, such as caffeic, ferulic, and *p*-coumaric acids, have recently been demonstrated to function as effective bulk oil antioxidants [75], while caffeic and ferulic acid derivatives displayed promising ability in protecting rapeseed oil and emulsions thereof from oxidation [76]. However, since PP polyphenols may also exert antimicrobial activity, PP extracts have also been considered as preservatives, acting as growth inhibitors for various microorganisms [70,71,77]. Finally, some other uses of specific PP constituents (CGA) have also been proposed, including in emulsification, color enhancement, food ingredient modification, and prebiotics [78].

5.2. Pharmaceutical Applications

As mentioned earlier in the text, a prime activity expressed by HCAs occurring in PPs is their antioxidant function, which may entail several other biochemical events. However, the pharmacological potency of HCAs that can be recovered from PPs goes beyond the antioxidant properties and implicates more complicated biological phenomena. Several works have reported the anti-inflammatory, analgesic, and antimicrobial effects of polyphenol-containing PP extracts, which reveal an assortment of potencies for these phytochemicals [79]. Furthermore, a range of structurally diversified HCAs and their derivatives have been extensively tested as cosmeceutical agents with high prospects in skin treatments as anti-aging and depigmentation actives [80]. Although PP extracts have in some instances been used as crude preparations, and despite the complexity of their polyphenolic composition, HCAs that have been frequently encountered in PPs, such as CGA, have been explicitly proposed as promising therapeutic agents in diseases such as diabetes and cancer [81], as well as for protection against cardiological, hepatological, and neurological disorders [30,35]. Major contributions to advancing knowledge on HCA bioactivities have been studies examining their metabolism and absorption by humans [23], as well as evidence that has emerged from epidemiological investigations [29]. Trials on pharmacokinetics have also played an instrumental role in this regard, identifying problems associated with the limited therapeutic use of certain HCAs (i.e., ferulic acid), due to poor solubility, brief plasma half-life, and low bioavailability, and the development of novel delivery systems [82].

5.3. Platform Chemicals for Biotransformations

HCAs derived from biowastes such as PPs are an abundant biomass feedstock, and although they may be directly used in the applications discussed above, their value can be significantly increased when they are further modified into high-added-value compounds. Thus, HCAs recovered from PPs could be essentially harnessed as platform chemicals and channeled towards the production of novel bio-based compounds with targeted chemical and/or biological properties to widen their applicability. Such an approach would support the techno-economic feasibility of producing HCAs on an industrial scale, reducing the associated production time and costs [83]. Thus, PPs may be considered as an agro-industrial waste that can be turned into a sustainable feedstock for biorefinery purposes. In this framework, HCAs could undergo biotransformations with specific enzymes for highly accurate, targeted structural modifications, such as esterification, decarboxylation,

reduction, transamination etc., to produce a variety of flavor and pharmaceutical substances [84]. In addition, the bound forms of these phenolic compounds can be effectively released through cell wall and glycoside hydrolysis by microbial enzymes. Then, they can be converted into unique biochemicals through microbial transformations including sulfate conjugation, methylation, hydroxylation, carboxylation, and oxidation during fermentative processes, thus generating a vast spectrum of metabolites that could be used as functional ingredients, flavor additives, and antioxidants [85]. Task-specific microbial HCA transformations have been proposed for the production of vinylphenols (4-vinylguaiacol, canolol, 4-vinylcatechol, and 4-vinylphenol), which are bioactive chemicals with several properties including anti-inflammatory, antioxidant, and antimicrobial activities, with significant potential applications in the food, pharmaceutical, and cosmetic industries [86].

6. Prospects and Potentialities

Potato processing industries and relevant activities generate a vast volume of potato peel as their principal waste product. Within the framework of a circular economy, several strategies have been proposed for the sustainable management of this side stream. Aside from exploitations such as animal feed, composting, and/or anaerobic digestion, which largely represent the main large-scale treatment routes, the higher-value options, such as the recovery and utilization of HCAs, are still in their infancy, investigated principally on a lab scale. Sustainable and high-profit harnessing of PPs dictates exploitation within the biorefinery concept, with the recovery of bioactive compounds being one of the prime objectives. Albeit tackled by several literature reports, the integrated biorefinery approach for PPs is far from being established. This is because there has been an important lack of instrumental examinations, with research in this area pertaining mainly to techno-economic studies, the development of cutting-edge green technologies for efficient HCA retrieval, and studies comprising larger scales (scale-up). However, potato processing waste should be regarded as one of the most promising waste biomass pools, given their worldwide occurrence and the amount generated on an annual basis. In this sense, PPs may be regarded as an underutilized side stream with high potential in biorefinery strategies. In support of this view, there are ongoing studies evidencing that biorefineries with large production capacities can be economically viable. On this ground, the production of high-added-value substances can further contribute to process viability due to their increased market value. On the other hand, pertinent examinations of the life cycle assessment of such processes have not been adequately addressed in the literature. Yet, such information would be pivotal for understanding and selecting the best practices for setting up efficient and viable large-scale valorization procedures for HCA production from PPs.

Keeping this in mind, the following research endeavors are proposed, with the view of shining more light onto higher-value options for PP valorization:

- Investigations on real potato processing waste should be top priority, in order to reliably depict the actual waste composition and draw credible conclusions. Studies carried out using laboratory-generated material (i.e., potato tuber peeling) may be misleading, since industrial waste could possess diversified attributes due to different processing conditions, partial spoilage ascribed to high moisture content, etc. In the same line, the effect of waste handling, e.g., drying, must be examined to record the actual effect of such treatments on the composition of bioactive constituents, considering that drying is an indispensable operation for safe storage and further waste processing.
- It is undisputed that there is a lack of data on the extraction of potato waste using innovative and green extraction methodologies. Although efforts have been expended to some extent on developing UAE, the majority of these protocols suffer from insuffi-

cient engineering basis, which would provide valuable information for scale-up trials. Furthermore, other techniques widely tested on other materials, such as the use of green deep eutectic solvents and pressurized liquids, have been scarcely employed for potato waste extraction. Thus, there is a need for the implementation of cutting-edge extraction technologies and their appraisal with regard to polyphenol recovery from potato side streams.

- Downstream processing is another issue that merits wider and more profound investigation. The general picture obtained by considering the studies reported in this review shows PP extracts to be largely dominated by CGA. On this basis, downstream procedures could be highly efficacious if CGA is to be isolated, since the other HCAs found in PP extracts usually occur at significantly lower levels. The merit deriving from such an approach would lie in the use of pure CGA as an additive, but also as a precursor to producing caffeic acid. Thus, in this case, compound-targeted processes may be deployed. On the other hand, considering that recent trends dictate the production of functionality-based rather than ingredient-based formulations, extracts without purification could be destined for general use (e.g., food antioxidants) rather than specific applications. This view might be appealing, because downstream operation steps could be limited, thereby reducing energy requirements and cost. Research advancement in this direction could offer unprecedented opportunities for alternative PP uses, as well as straight-forward scale-up for delivering commodities of wider applicability.
- The use of HCAs as feed for enzymic and/or microbial transformations has certainly paved the way for novel product development. In this framework, the exploration of routes for synthesizing derivatives with specific properties for targeted valorization is imminent. Some examples to mention include the enzyme-mediated production of lipophilic esters for antioxidants in lipid foods, the generation of bio-based pigments through oxidative reactions, and protein cross-linking for the modification of the rheological properties of foods.

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References

1. Jiménez-Moreno, N.; Esparza, I.; Bimbela, F.; Gandía, L.M.; Ancín-Azpilicueta, C. Valorization of selected fruit and vegetable wastes as bioactive compounds: Opportunities and challenges. *Crit. Rev. Environ. Sci. Technol.* **2020**, *50*, 2061–2108. [\[CrossRef\]](#)
2. Roselli, V.; Pugliese, G.; Leuci, R.; Brunetti, L.; Gambacorta, L.; Tufarelli, V.; Piemontese, L. Green methods to recover bioactive compounds from food industry waste: A sustainable practice from the perspective of the circular economy. *Molecules* **2024**, *29*, 2682. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Esparza, I.; Jiménez-Moreno, N.; Bimbela, F.; Ancín-Azpilicueta, C.; Gandía, L.M. Fruit and vegetable waste management: Conventional and emerging approaches. *J. Environ. Manag.* **2020**, *265*, 110510. [\[CrossRef\]](#)
4. Rashwan, A.K.; Bai, H.; Osman, A.I.; Eltohamy, K.M.; Chen, Z.; Younis, H.A.; Al-Fatesh, A.; Rooney, D.W.; Yap, P.-S. Recycling food and agriculture by-products to mitigate climate change: A review. *Environ. Chem. Lett.* **2023**, *21*, 3351–3375. [\[CrossRef\]](#)
5. Monteiro, A.R.; Battisti, A.P.; Valencia, G.A.; de Andrade, C.J. The production of high-added-value bioproducts from non-conventional biomasses: An overview. *Biomass* **2023**, *3*, 123–137. [\[CrossRef\]](#)
6. Jimenez-Lopez, C.; Fraga-Corral, M.; Carpena, M.; García-Oliveira, P.; Echave, J.; Pereira, A.; Lourenço-Lopes, C.; Prieto, M.; Simal-Gandara, J. Agriculture waste valorisation as a source of antioxidant phenolic compounds within a circular and sustainable bioeconomy. *Food Funct.* **2020**, *11*, 4853–4877. [\[CrossRef\]](#)
7. Sorrenti, V.; Burò, I.; Consoli, V.; Vanella, L. Recent advances in health benefits of bioactive compounds from food wastes and by-products: Biochemical aspects. *Int. J. Mol. Sci.* **2023**, *24*, 2019. [\[CrossRef\]](#)

8. Banerjee, J.; Singh, R.; Vijayaraghavan, R.; MacFarlane, D.; Patti, A.F.; Arora, A. Bioactives from fruit processing wastes: Green approaches to valuable chemicals. *Food Chem.* **2017**, *225*, 10–22. [\[CrossRef\]](#)
9. Barbera, M. Reuse of food waste and wastewater as a source of polyphenolic compounds to use as food additives. *J. AOAC Int.* **2020**, *103*, 906–914. [\[CrossRef\]](#)
10. Osorio, L.L.D.R.; Flórez-López, E.; Grande-Tovar, C.D. The potential of selected agri-food loss and waste to contribute to a circular economy: Applications in the food, cosmetic and pharmaceutical industries. *Molecules* **2021**, *26*, 515. [\[CrossRef\]](#)
11. Krzyżostan, M.; Wawrzyńczak, A.; Nowak, I. Use of waste from the food industry and applications of the fermentation process to create sustainable cosmetic products: A review. *Sustainability* **2024**, *16*, 2757. [\[CrossRef\]](#)
12. Vilas-Franquesa, A.; Casertano, M.; Tresserra-Rimbau, A.; Vallverdú-Queralt, A.; Torres-León, C. Recent advances in bio-based extraction processes for the recovery of bound phenolics from agro-industrial by-products and their biological activity. *Crit. Rev. Food Sci. Nutr.* **2024**, *64*, 10643–10667. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Ben-Othman, S.; Jöudu, I.; Bhat, R. Bioactives from agri-food wastes: Present insights and future challenges. *Molecules* **2020**, *25*, 510. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Yadav, S.; Malik, K.; Moore, J.M.; Kamboj, B.R.; Malik, S.; Malik, V.K.; Arya, S.; Singh, K.; Mahanta, S.; Bishnoi, D.K. Valorisation of agri-food waste for bioactive compounds: Recent trends and future sustainable challenges. *Molecules* **2024**, *29*, 2055. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Khanal, S.; Karimi, K.; Majumdar, S.; Kumar, V.; Verma, R.; Bhatia, S.K.; Kuca, K.; Esteban, J.; Kumar, D. Sustainable utilization and valorization of potato waste: State of the art, challenges, and perspectives. *Biomass Convers. Biorefin.* **2024**, *14*, 23335–23360. [\[CrossRef\]](#)
16. Rodríguez-Martínez, B.; Gullón, B.; Yáñez, R. Identification and recovery of valuable bioactive compounds from potato peels: A comprehensive review. *Antioxidants* **2021**, *10*, 1630. [\[CrossRef\]](#)
17. Akyol, H.; Riciputi, Y.; Capanoglu, E.; Caboni, M.F.; Verardo, V. Phenolic compounds in the potato and its byproducts: An overview. *Int. J. Mol. Sci.* **2016**, *17*, 835. [\[CrossRef\]](#)
18. Salem, M.A.; Mansour, H.E.A.; Mosalam, E.M.; El-Shiekh, R.A.; Ezzat, S.M.; Zayed, A. Valorization of by-products derived from onions and potato: Extraction optimization, metabolic profile, outstanding bioactivities, and industrial applications. *Waste Biomass Valor.* **2023**, *14*, 1823–1858. [\[CrossRef\]](#)
19. Eliopoulos, C.; Markou, G.; Langousi, I.; Arapoglou, D. Reintegration of food industry by-products: Potential applications. *Foods* **2022**, *11*, 3743. [\[CrossRef\]](#)
20. Calcio Gaudino, E.; Colletti, A.; Grillo, G.; Tabasso, S.; Cravotto, G. Emerging processing technologies for the recovery of valuable bioactive compounds from potato peels. *Foods* **2020**, *9*, 1598. [\[CrossRef\]](#)
21. da Silva, A.P.G.; Sganzerla, W.G.; John, O.D.; Marchiosi, R. A comprehensive review of the classification, sources, biosynthesis, and biological properties of hydroxybenzoic and hydroxycinnamic acids. *Phytochem. Rev.* **2023**, 1–30. [\[CrossRef\]](#)
22. Shahidi, F.; Chandrasekara, A. Hydroxycinnamates and their *in vitro* and *in vivo* antioxidant activities. *Phytochem. Rev.* **2010**, *9*, 147–170. [\[CrossRef\]](#)
23. El-Seedi, H.R.; El-Said, A.M.; Khalifa, S.A.; Goransson, U.; Bohlin, L.; Borg-Karlson, A.-K.; Verpoorte, R. Biosynthesis, natural sources, dietary intake, pharmacokinetic properties, and biological activities of hydroxycinnamic acids. *J. Agric. Food Chem.* **2012**, *60*, 10877–10895. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Bunzel, M. Chemistry and occurrence of hydroxycinnamate oligomers. *Phytochem. Rev.* **2010**, *9*, 47–64. [\[CrossRef\]](#)
25. Frosi, I.; Montagna, I.; Colombo, R.; Milanese, C.; Papetti, A. Recovery of chlorogenic acids from agri-food wastes: Updates on green extraction techniques. *Molecules* **2021**, *26*, 4515. [\[CrossRef\]](#)
26. Wianowska, D.; Gil, M. Recent advances in extraction and analysis procedures of natural chlorogenic acids. *Phytochem. Rev.* **2019**, *18*, 273–302. [\[CrossRef\]](#)
27. Teixeira, J.; Gaspar, A.; Garrido, E.M.; Garrido, J.; Borges, F. Hydroxycinnamic acid antioxidants: An electrochemical overview. *BioMed Res. Int.* **2013**, *2013*, 251754. [\[CrossRef\]](#)
28. Chen, J.; Yang, J.; Ma, L.; Li, J.; Shahzad, N.; Kim, C.K. Structure-antioxidant activity relationship of methoxy, phenolic hydroxyl, and carboxylic acid groups of phenolic acids. *Sci. Rep.* **2020**, *10*, 2611.
29. Coman, V.; Vodnar, D.C. Hydroxycinnamic acids and human health: Recent advances. *J. Sci. Food Agric.* **2020**, *100*, 483–499. [\[CrossRef\]](#)
30. Sova, M.; Saso, L. Natural sources, pharmacokinetics, biological activities and health benefits of hydroxycinnamic acids and their metabolites. *Nutrients* **2020**, *12*, 2190. [\[CrossRef\]](#)
31. Contardi, M.; Lenzuni, M.; Fiorentini, F.; Summa, M.; Bertorelli, R.; Suarato, G.; Athanassiou, A. Hydroxycinnamic acids and derivatives formulations for skin damages and disorders: A review. *Pharmaceutics* **2021**, *13*, 999. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Ou, S.; Kwok, K.C. Ferulic acid: Pharmaceutical functions, preparation and applications in foods. *J. Sci. Food Agric.* **2004**, *84*, 1261–1269. [\[CrossRef\]](#)

33. Mancuso, C.; Santangelo, R. Ferulic acid: Pharmacological and toxicological aspects. *Food Chem. Toxicol.* **2014**, *65*, 185–195. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Naveed, M.; Hejazi, V.; Abbas, M.; Kamboh, A.A.; Khan, G.J.; Shumzaid, M.; Ahmad, F.; Babazadeh, D.; Xia, F.F.; Modarresi-Ghazani, F. Chlorogenic acid (CGA): A pharmacological review and call for further research. *Biomed. Pharmacother.* **2018**, *97*, 67–74. [\[CrossRef\]](#)
35. Li, Z.; Niu, L.; Chen, Y.; Qiu, X.; Du, T.; Zhu, M.; Wang, M.; Mo, H.; Xiao, S. Recent advance in the biological activity of chlorogenic acid and its application in food industry. *Int. J. Food Sci. Technol.* **2023**, *58*, 4931–4947. [\[CrossRef\]](#)
36. Onyeneho, S.N.; Hettiarachchy, N.S. Antioxidant activity, fatty acids and phenolic acids compositions of potato peels. *J. Sci. Food Agric.* **1993**, *62*, 345–350. [\[CrossRef\]](#)
37. De Sotillo, D.R.; Hadley, M.; Holm, E. Phenolics in aqueous potato peel extract: Extraction, identification and degradation. *J. Food Sci.* **1994**, *59*, 649–651. [\[CrossRef\]](#)
38. Kanatt, S.R.; Chander, R.; Radhakrishna, P.; Sharma, A. Potato peel extract a natural antioxidant for retarding lipid peroxidation in radiation processed lamb meat. *J. Agric. Food Chem.* **2005**, *53*, 1499–1504. [\[CrossRef\]](#)
39. Nara, K.; Miyoshi, T.; Honma, T.; Koga, H. Antioxidative activity of bound-form phenolics in potato peel. *Biosci. Biotechnol. Biochem.* **2006**, *70*, 1489–1491. [\[CrossRef\]](#)
40. Leo, L.; Leone, A.; Longo, C.; Lombardi, D.A.; Raimo, F.; Zacheo, G. Antioxidant compounds and antioxidant activity in “early potatoes”. *J. Agric. Food Chem.* **2008**, *56*, 4154–4163. [\[CrossRef\]](#)
41. Al-Weshahy, A.; Rao, A.V. Isolation and characterization of functional components from peel samples of six potatoes varieties growing in Ontario. *Food Res. Int.* **2009**, *42*, 1062–1066. [\[CrossRef\]](#)
42. Deußer, H.; Guignard, C.; Hoffmann, L.; Evers, D. Polyphenol and glycoalkaloid contents in potato cultivars grown in Luxembourg. *Food Chem.* **2012**, *135*, 2814–2824. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Valiñas, M.A.; Lanteri, M.L.; Ten Have, A.; Andreu, A.B. Chlorogenic acid, anthocyanin and flavan-3-ol biosynthesis in flesh and skin of Andean potato tubers (*Solanum tuberosum* subsp. andigena). *Food Chem.* **2017**, *229*, 837–846. [\[CrossRef\]](#) [\[PubMed\]](#)
44. Silva-Beltrán, N.P.; Chaidez-Quiroz, C.; López-Cuevas, O.; Ruiz-Cruz, S.; López-Mata, M.A.; Del-Toro-Sánchez, C.L.; Marquez-Rios, E.; Ornelas-Paz, J.D.J. Phenolic compounds of potato peel extracts: Their antioxidant activity and protection against human enteric viruses. *J. Microb. Biotechnol.* **2017**, *27*, 234–241. [\[CrossRef\]](#)
45. Shaheen, S.; Grigorakis, S.; Halahlah, A.; Loupassaki, S.; Makris, D.P. Extractor dimensions affect optimization of laboratory-scale batch solid-liquid extraction of polyphenols from plant material: Potato peels as a case study. *Chem. Eng. Commun.* **2021**, *208*, 1618–1629. [\[CrossRef\]](#)
46. Casasni, S.; Guenaoui, A.; Grigorakis, S.; Makris, D.P. Acid-Catalyzed organosolv treatment of potato peels to boost release of polyphenolic compounds using 1-and 2-Propanol. *Appl. Sci.* **2023**, *13*, 9484. [\[CrossRef\]](#)
47. Almeida, P.V.; Costa, J.C.; Gando-Ferreira, L.M.; Quina, M.J. Effect of drying and milling industrial potato peel for recovering phenolic and antioxidant compounds: Optimization process and economic evaluation. *J. Ind. Eng. Chem.* **2024**, *140*, 385–397. [\[CrossRef\]](#)
48. Helmi, L.; Al Khatib, A.; Rajha, H.N.; Debs, E.; Jammoul, A.; Louka, N.; El Darra, N. Valorization of potato peels (*Solanum tuberosum*) using infrared-assisted extraction: A novel sprouting suppressant and antibacterial agent. *Foods* **2024**, *13*, 3445. [\[CrossRef\]](#)
49. Smyrnakis, G.; Stamoulis, G.; Palaiogiannis, D.; Chatzimitakos, T.; Athanasiadis, V.; Lalas, S.I.; Makris, D.P. Recovery of polyphenolic antioxidants from coffee silverskin using acid-catalyzed ethanol organosolv treatment. *ChemEngineering* **2023**, *7*, 72. [\[CrossRef\]](#)
50. Morsli, F.; Grigorakis, S.; Halahlah, A.; Poulaniiti, K.P.; Makris, D.P. Appraisal of the combined effect of time and temperature on the total polyphenol yield in batch stirred-tank extraction of medicinal and aromatic plants: The extraction efficiency factor. *J. Appl. Res. Med. Arom. Plants* **2021**, *25*, 100340. [\[CrossRef\]](#)
51. Rasheed, H.; Ahmad, D.; Bao, J. Genetic diversity and health properties of polyphenols in potato. *Antioxidants* **2022**, *11*, 603. [\[CrossRef\]](#) [\[PubMed\]](#)
52. Albishi, T.; John, J.A.; Al-Khalifa, A.S.; Shahidi, F. Phenolic content and antioxidant activities of selected potato varieties and their processing by-products. *J. Funct. Foods* **2013**, *5*, 590–600. [\[CrossRef\]](#)
53. Maldonado, A.F.S.; Mudge, E.; Gänzle, M.G.; Schieber, A. Extraction and fractionation of phenolic acids and glycoalkaloids from potato peels using acidified water/ethanol-based solvents. *Food Res. Int.* **2014**, *65*, 27–34. [\[CrossRef\]](#)
54. Paleologou, I.; Vasiliou, A.; Grigorakis, S.; Makris, D.P. Optimisation of a green ultrasound-assisted extraction process for potato peel (*Solanum tuberosum*) polyphenols using bio-solvents and response surface methodology. *Biomass Convers. Biorefin.* **2016**, *6*, 289–299. [\[CrossRef\]](#)
55. Kumari, B.; Tiwari, B.K.; Hossain, M.B.; Rai, D.K.; Brunton, N.P. Ultrasound-assisted extraction of polyphenols from potato peels: Profiling and kinetic modelling. *Int. J. Food Sci. Technol.* **2017**, *52*, 1432–1439. [\[CrossRef\]](#)

56. Riciputi, Y.; Diaz-de-Cerio, E.; Akyol, H.; Capanoglu, E.; Cerretani, L.; Caboni, M.F.; Verardo, V. Establishment of ultrasound-assisted extraction of phenolic compounds from industrial potato by-products using response surface methodology. *Food Chem.* **2018**, *269*, 258–263. [\[CrossRef\]](#)
57. Makori, S.I.; Mu, T.-H.; Sun, H.-N. Profiling of polyphenols, flavonoids and anthocyanins in potato peel and flesh from four potato varieties. *Potato Res.* **2022**, *65*, 193–208. [\[CrossRef\]](#)
58. Mangiapelo, L.; Blasi, F.; Ianni, F.; Barola, C.; Galarini, R.; Abualzulof, G.W.; Sardella, R.; Volpi, C.; Cossignani, L. Optimization of ultrasound-assisted extraction of chlorogenic acid from potato sprout waste and enhancement of the in vitro total antioxidant capacity. *Antioxidants* **2023**, *12*, 348. [\[CrossRef\]](#)
59. Tiwari, B.K. Ultrasound: A clean, green extraction technology. *Trends Anal. Chem.* **2015**, *71*, 100–109. [\[CrossRef\]](#)
60. Chemat, F.; Rombaut, N.; Sicaire, A.-G.; Meullemiestre, A.; Fabiano-Tixier, A.-S.; Abert-Vian, M. Ultrasound assisted extraction of food and natural products. Mechanisms, techniques, combinations, protocols and applications. A review. *Ultrason. Sonochem.* **2017**, *34*, 540–560. [\[CrossRef\]](#)
61. Joly, N.; Souidi, K.; Depraetere, D.; Wils, D.; Martin, P. Potato by-products as a source of natural chlorogenic acids and phenolic compounds: Extraction, characterization, and antioxidant capacity. *Molecules* **2020**, *26*, 177. [\[CrossRef\]](#) [\[PubMed\]](#)
62. Nardini, M.; Cirillo, E.; Natella, F.; Mencarelli, D.; Comisso, A.; Scaccini, C. Detection of bound phenolic acids: Prevention by ascorbic acid and ethylenediaminetetraacetic acid of degradation of phenolic acids during alkaline hydrolysis. *Food Chem.* **2002**, *79*, 119–124. [\[CrossRef\]](#)
63. Singh, A.; Sabally, K.; Kubow, S.; Donnelly, D.J.; Gariepy, Y.; Orsat, V.; Raghavan, G. Microwave-assisted extraction of phenolic antioxidants from potato peels. *Molecules* **2011**, *16*, 2218–2232. [\[CrossRef\]](#) [\[PubMed\]](#)
64. Singh, P.P.; Saldaña, M.D. Subcritical water extraction of phenolic compounds from potato peel. *Food Res. Int.* **2011**, *44*, 2452–2458. [\[CrossRef\]](#)
65. Manousaki, A.; Jancheva, M.; Grigorakis, S.; Makris, D.P. Extraction of antioxidant phenolics from agri-food waste biomass using a newly designed glycerol-based natural low-transition temperature mixture: A comparison with conventional eco-friendly solvents. *Recycling* **2016**, *1*, 194–204. [\[CrossRef\]](#)
66. Frontuto, D.; Carullo, D.; Harrison, S.; Brunton, N.; Ferrari, G.; Lyng, J.; Pataro, G. Optimization of pulsed electric fields-assisted extraction of polyphenols from potato peels using response surface methodology. *Food Bioproc. Technol.* **2019**, *12*, 1708–1720. [\[CrossRef\]](#)
67. Lakka, A.; Lalas, S.; Makris, D.P. Development of a low-temperature and high-performance green extraction process for the recovery of polyphenolic phytochemicals from waste potato peels using hydroxypropyl β -cyclodextrin. *Appl. Sci.* **2020**, *10*, 3611. [\[CrossRef\]](#)
68. de Andrade Lima, M.; Andreou, R.; Charalampopoulos, D.; Chatzifragkou, A. Supercritical carbon dioxide extraction of phenolic compounds from potato (*Solanum tuberosum*) peels. *Appl. Sci.* **2021**, *11*, 3410. [\[CrossRef\]](#)
69. Makris, D.P.; Boskou, D. Plant-derived antioxidants as food additives. *Plants Source Nat. Antioxid.* **2014**, *398*, 169–190.
70. Sampaio, S.L.; Petropoulos, S.A.; Alexopoulos, A.; Heleno, S.A.; Santos-Buelga, C.; Barros, L.; Ferreira, I.C. Potato peels as sources of functional compounds for the food industry: A review. *Trends Food Sci. Technol.* **2020**, *103*, 118–129. [\[CrossRef\]](#)
71. Torres, M.D.; Domínguez, H. Valorisation of potato wastes. *Int. J. Food Sci. Technol.* **2020**, *55*, 2296–2304. [\[CrossRef\]](#)
72. Jimenez-Champi, D.; Romero-Oregon, F.L.; Moran-Reyes, A.; Muñoz, A.M.; Ramos-Escudero, F. Bioactive compounds in potato peels, extraction methods, and their applications in the food industry: A review. *CyTa J. Food* **2023**, *21*, 418–432. [\[CrossRef\]](#)
73. Samotyja, U. Potato peel as a sustainable resource of natural antioxidants for the food industry. *Potato Res.* **2019**, *62*, 435–451. [\[CrossRef\]](#)
74. Brahmi, F.; Mateos-Aparicio, I.; Garcia-Alonso, A.; Abaci, N.; Saoudi, S.; Smail-Benazzouz, L.; Guemghar-Haddadi, H.; Madani, K.; Boulekbache-Makhlouf, L. Optimization of conventional extraction parameters for recovering phenolic compounds from potato (*Solanum tuberosum* L.) peels and their application as an antioxidant in yogurt formulation. *Antioxidants* **2022**, *11*, 1401. [\[CrossRef\]](#)
75. Trajkovska, M.; Derwiche, F.; Grigorakis, S.; Makris, D.P. Natural phenolic acids as effective bulk oil antioxidants: Oxidative stability modeling using olive kernel oil as a case study. *Appl. Sci.* **2024**, *14*, 6508. [\[CrossRef\]](#)
76. Rabiej-Kozioł, D.; Krzemiński, M.P.; Szydłowska-Czerniak, A. Synthesis of steryl hydroxycinnamates to enhance antioxidant activity of rapeseed oil and emulsions. *Materials* **2020**, *13*, 4536. [\[CrossRef\]](#)
77. Gebrechistos, H.Y.; Chen, W. Utilization of potato peel as eco-friendly products: A review. *Food Sci. Nutr.* **2018**, *6*, 1352–1356. [\[CrossRef\]](#)
78. Wang, L.; Pan, X.; Jiang, L.; Chu, Y.; Gao, S.; Jiang, X.; Zhang, Y.; Chen, Y.; Luo, S.; Peng, C. The biological activity mechanism of chlorogenic acid and its applications in food industry: A review. *Front. Nutr.* **2022**, *9*, 943911. [\[CrossRef\]](#)
79. Hidayat, W.; Sufiawati, I.; Satari, M.H.; Lesmana, R.; Ichwan, S. Pharmacological activity of chemical compounds of potato peel waste (*Solanum tuberosum* L.) in vitro: A scoping review. *J. Exper. Pharmacol.* **2024**, *16*, 61–69. [\[CrossRef\]](#)

80. Taofiq, O.; González-Paramás, A.M.; Barreiro, M.F.; Ferreira, I.C. Hydroxycinnamic acids and their derivatives: Cosmeceutical significance, challenges and future perspectives, a review. *Molecules* **2017**, *22*, 281. [\[CrossRef\]](#)
81. Kumar, N.; Goel, N. Phenolic acids: Natural versatile molecules with promising therapeutic applications. *Biotechnol. Rep.* **2019**, *24*, e00370. [\[CrossRef\]](#) [\[PubMed\]](#)
82. Raj, N.D.; Singh, D. A critical appraisal on ferulic acid: Biological profile, biopharmaceutical challenges and nano formulations. *Health Sci. Rev.* **2022**, *5*, 100063. [\[CrossRef\]](#)
83. Grajales-Hernández, D.A.; Ruiz, M.A.A.; Contreras-Jáquez, V.; Mateos-Díaz, J.C. Biotransformation of phenolic acids from by-products using heterogeneous biocatalysts: One more step toward a circular economy. *Curr. Opin. Green Sustain. Chem.* **2021**, *32*, 100550. [\[CrossRef\]](#)
84. Tinikul, R.; Chenprakhon, P.; Maenpuen, S.; Chaiyen, P. Biotransformation of plant-derived phenolic acids. *Biotechnol. J.* **2018**, *13*, e1700632. [\[CrossRef\]](#)
85. Gulsunoglu-Konuskan, Z.; Kilic-Akyilmaz, M. Microbial bioconversion of phenolic compounds in agro-industrial wastes: A review of mechanisms and effective factors. *J. Agric. Food Chem.* **2022**, *70*, 6901–6910. [\[CrossRef\]](#)
86. Lomascolo, A.; Odinet, E.; Villeneuve, P.; Lecomte, J. Challenges and advances in biotechnological approaches for the synthesis of canolol and other vinylphenols from biobased *p*-hydroxycinnamic acids: A review. *Biotechnol. Biofuels Bioprod.* **2023**, *16*, 173. [\[CrossRef\]](#)

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