

REVIEW

Overview of garlic waste management, circular economy and upcycling

Perspectivas de la gestión de residuos del ajo, economía circular y transformación

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ABSTRACT

In the last three years, 2 billion tonnes of untreated and dismissed agricultural wastes have been accumulated without adequate management of reuse or final disposal, resulting in dumping or burning. The circular economy concept has gained increasing global recognition for addressing environmental and economic challenges. Garlic, the second most common bulb vegetable cultivated worldwide, generates significant waste during its industrial processing, including husks, stalks, straws, and leaves. These wastes, representing 3.0 to 3.7 million tonnes of residual biomass per year, are currently underutilised, with the usual treatment involving dumping in landfills or direct burning, leading to increased soil and air pollution. In this review, we aim to encourage innovation by presenting a search for state-of-the-art garlic waste management. We identified studies about garlic residual biomass valorisation as raw material for obtaining different extracts and polymers, even energy or biofuels. Finally, following circular economy principles, we propose potential uses for garlic by-products to be repurposed or upcycled as materials within agricultural or other production chains. The information above reveals an increasing demand and interest in garlic waste valorisation. Future studies are needed to exploit garlic by-products as important sources of biopolymers and phytochemicals.

Keywords

bioactive compounds • biopolymers • circular economy • garlic waste • organosulfur compounds • pectin • valorisation

RESUMEN

En los últimos tres años, se han acumulado 2 mil millones de toneladas de residuos agrícolas no tratados y desechados sin una adecuada gestión o disposición final para su reutilización, resultando en vertederos de basura o siendo quemados. El concepto de economía circular cada vez ha ganado mayor reconocimiento mundial para abordar desafíos ambientales y económicos. El ajo, siendo la segunda hortaliza más cultivada en el mundo, durante su procesamiento industrial genera cantidades significativas de catáfilas (piel), tallos, paja y hojas. Dichos residuos, que representan de 3,0 a 3,7 millones de toneladas de biomasa residual por año, actualmente son subutilizados. El tratamiento convencional es disponerlos en vertederos o quemarlos directamente, aumentando la contaminación del aire y el suelo. En este trabajo nuestro objetivo es fomentar la innovación presentando una búsqueda del estado del arte en la gestión de residuos del ajo. Identificamos estudios sobre la valorización de biomasa residual de ajo como materia prima para obtener diferentes extractos y polímeros, incluso para la obtención de energía. Finalmente, de acuerdo con los principios de economía circular, proponemos posibles usos de los subproductos del ajo para su reutilización o transformación como materias agrícolas o en otras cadenas productivas. La información anterior revela una demanda y un interés creciente en la valorización de los residuos de ajo. Se necesitan estudios futuros para investigar y explotar aún más los subproductos del ajo como fuentes valiosas de biopolímeros y fitoquímicos.

Palabras clave

compuestos bioactivos • biopolímeros • economía circular • residuos del ajo • compuestos organosulfurados • pectina • valorización

INTRODUCTION

Nowadays, there is a global awareness of the problems derived from accumulating residues from agricultural production and their environmental impact. For example, in only three years, 3.9 billion tons of biomass can be produced (5, 65), accumulating 2 billion tons of untreated residues from the agriculture industry (55, 79). Given the world population growth and the expansion of new cultivation areas, these numbers are expected to increase in the following years. With 10 billion people by 2050, global waste growth will rise to 70%, increasing the impact on the food system from 50% to 90% (39). For this reason, the study

of agro-industrial waste worldwide production, valorisation and, employment for other purposes become important topics of study.

Among the wastes of agricultural production, we are focusing on the by-products derived from the cultivation and industrialisation of garlic (*Allium sativum* L.). The global garlic commerce is reflected by its high consumption per capita (7.6 kg by 2018) and a significant cultivated area (1.546.741 ha), harvesting 28.49 million tonnes with a world average productivity of 18.4 t/ha (19). China, Spain, and Argentina are the leading garlic producers and exporters, representing almost 90.8% of the global sales market (48). The commercial context estimates that garlic cultivation will increase in the coming years, reaching 31.1 million tonnes per year by 2025 (28), with an annual average growth of 4.72% (22). This vegetable is sold as fresh or industrialised products such as paste, dehydrated, powder, essential oil, oil macerated, and aged extract. However, the industrial process dismisses 25-30% of solid waste (16, 38). Garlic harvesting has implicit waste generation in cleaning, cutting, drying and processing, to obtain phytochemicals and dietary supplements. These facts increase residual biomass tons with no responsible disposal, generating over 3.7 million tonnes of by-products annually (80).

Beyond garlic's culinary use, it is known for its relevant biological and medicinal properties, contributing to its increasing demand, reaching 28 million tons in 2020 (80). Garlic properties and biological activities have been widely studied, demonstrating its preventive effect against chronic diseases such as cancer, antithrombotic (25), antibacterial, antifungal, and antiviral (40, 78, 83). These properties have been attributed to their composition in organosulfur and phenolic compounds. This factor has significantly bolstered the surge in demand to generate medicinal and functional products.

The emergence of the circular economy concept gained traction in the 1980s, advocating for an economic model that prioritizes resource optimisation, waste reduction, environmental preservation, and fosters innovation (73). At its core lies the principles of waste reduction, reuse, recycling, and resource recovery. Upcycling, as a part of the circular economy, promotes waste reduction by reusing existing materials, encouraging creativity and innovation to generate higher-value products without relying on new resources (77). The potential of garlic waste to generate higher-value products offers a promising outlook for waste management. These principles aim to minimize waste and maximize value from products, materials, and resources, inspiring strategies to mitigate ecological issues.

Thus, in this review, we summarize some effective strategies for waste management and explore the potential use of garlic waste as value-added by-products, intending to hopefully define future research direction. The data collection was conducted using academic databases such as Scopus and Google Scholar; the information was organised and summarised to identify research gaps and facilitate the approach to this problem. In agreement with Elsevier's abstract and citation database Scopus, a search was done over the last 10 years using the keywords "garlic" and "wastes". We then selected studies focusing on garlic husks, straws, or both. The previous Scopus search was complemented by another in Google Scholar, which used keywords such as 'garlic wastes,' 'garlic husks and straws,' and 'agro-industrial garlic wastes. Other investigations consulted in Google Academics were also considered to discuss garlic waste treatment for the extraction of different polysaccharides and polymers.

Garlic wastes

Waste generation begins before the garlic harvesting process, starting with removing garlic scapes to enhance bulb growth and development. Figure 1 (page 218), details garlic residual biomass production. The matured garlic bulbs are harvested, undergoing a curing process (35°C, 2 weeks), and finally stored in sheds under ambient conditions for 2 months. Garlic packing sheds are facilities dedicated to the processing and preparation of garlic before distribution and sale. Some common tasks performed in the sheds include sorting, selection, cleaning, and packaging. Consequently, a large amount of waste is generated, mainly from stems and roots are used for energy, animal feedstock, and bio-compost (12). Unfortunately, a relevant part of garlic waste is disposed of in landfills (38). Meanwhile, dry garlic is used for direct consumption and processed spice products, an important commodity with relevant economic value (84).

Figure 1 also shows that industrial processing starts with crushing garlic bulbs and

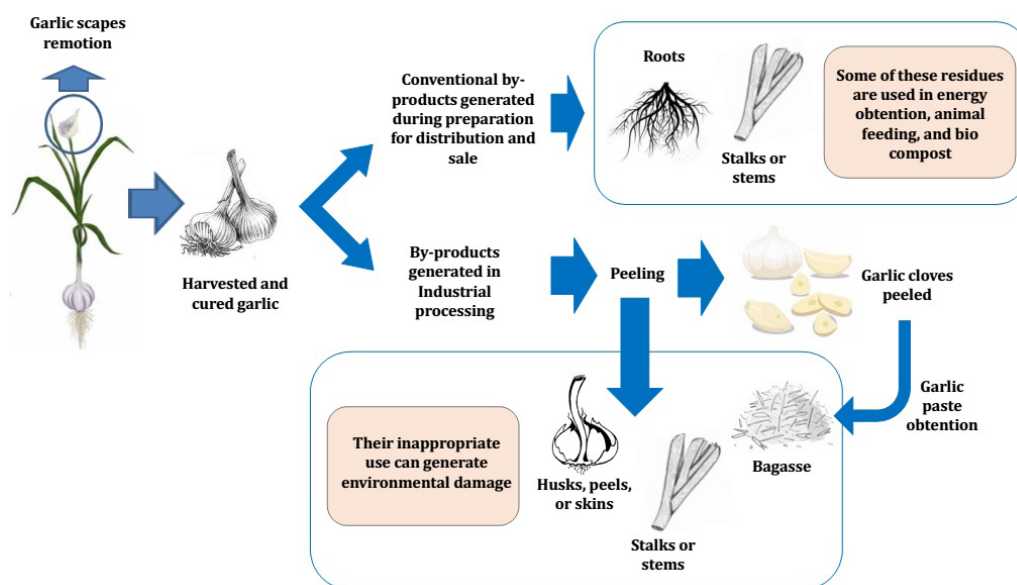


Figure 1. Scheme of wastes produced during garlic harvesting and processing
Figura 1. Esquema de los residuos generados durante la cosecha y procesamiento del ajo.

peeling them to obtain residual husks and straws (52). After the peeling, 25 to 30% of inedible parts are considered solid wastes, consisting mainly of dried stems (stalks) and peels (outer and inner husks) (16, 21). Garlic stalks represent 10%, and husks reach 25% of the total garlic weight in these solid wastes (14, 69). In the garlic paste industry, a dried pulpy residue called bagasse is obtained; however, there is currently no information about the residues generated in this process. In this way, low reuse and valorisation of garlic wastes negatively impact the agricultural ecosystem, e.g., untreated garlic residues are directly burned increasing the environmental impacts on soils and air (76).

Fortunately, in the last decade, different investigations have focused on garlic by-product valorisation for obtaining diverse bio-compounds and finding other ways to process them to mitigate their environmental impacts. Additionally, circular economy, as a current strategy, focusing on agro-industrial waste reduction by using them as raw materials in other value chains. As a result, bio-products and bio-energy are now being produced from wastes, improving the environmental quality (6). For example, garlic residual biomass has been used in biorefinery for energy generation and bioethanol production due to its chemical composition.

A circular economy, in concordance with Sustainable Development Goals (SDGs), is more specifically on sustainable consumption and production and climate change, which has a crucial role in waste management, changing the way from a linear economy to a circular one (92). In this sense, figure 2 (page 219) compares the traditional and modern ways of conceiving garlic waste treatment. One of these is based on linear economy or by-products conventional disposal derived from garlic, resulting in dumping, burning, and even animal feeding. The second strategy for solving the inappropriate use of garlic by-products is to consider a circular economy, obtaining bio-products and bioenergy from them.

Our search covered the last 10 years of publications with the keywords “garlic” and “wastes” on both Scopus and Google Academic databases. The data showed that garlic husks, peels, and skins (63%) are the most studied by-products, followed by garlic stems or stalks (23%). Finally, other garlic wastes are either not specified or are a mixture (figure 3, page 219).

Accordingly, in recent years the main uses of garlic waste have been related to

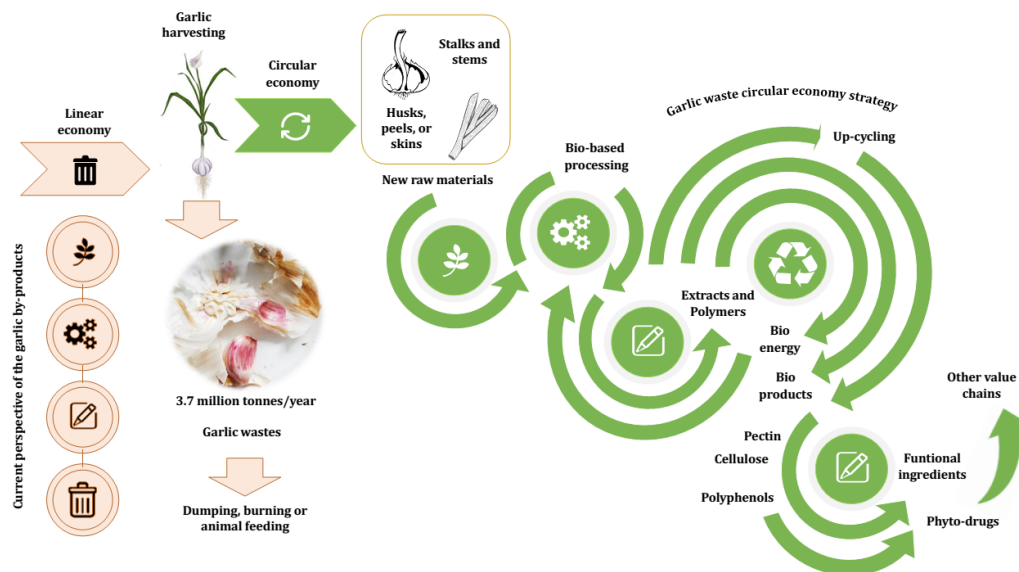


Figure 2. Comparison between the current disposition of by-products vs circular economy strategy.

Figura 2. Comparación de la disposición actual de subproductos contra una estrategia de economía circular.

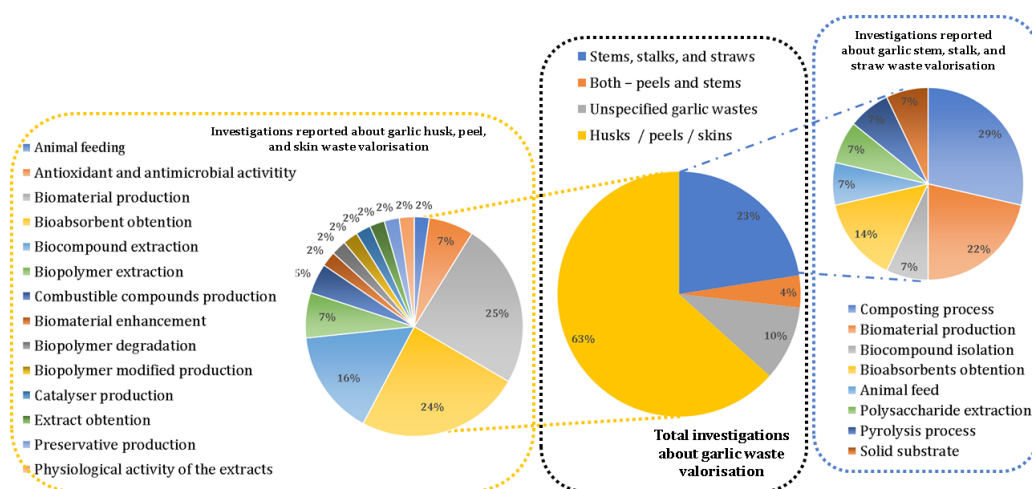


Figure 3. Results of the bibliography search regarding the kind of garlic waste and the objective of valorisation studied.

Figura 3. Resultados de la búsqueda bibliográfica mostrando el tipo de residuo de ajo y el objetivo de valorización estudiado.

second-generation products, minimising the negative impact on the food supply by harnessing resources that would otherwise be considered waste. These untreated materials are advantageously used as biomaterial and bio-adsorbent to remediate environmental pollution. Similarly, some approaches align with the circular economy using garlic by-products as solid substrates and in composting processes. In this context, some studies, improving extraction techniques have obtained bioactive compounds and bio-polymers showing innovative potential as bio-products, given their functional and

biological activity. Cellulose is the most common bio-polymer investigated and extracted from garlic straw wastes. However, other understudied bio-polymers are polysaccharides and dietary fibre such as pectin.

Research on garlic husks and straws for waste valorisation began several years ago. Research aimed to provide potential uses for these by-products, transforming them into value-added products, highlighting garlic biomass as a low-cost alternative.

Garlic by-products' main uses

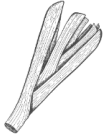
Use as biomaterial and bio-adsorbent production

According to the references detailed in table 1, garlic waste is mainly used as biomaterial or bio-adsorbent. Husk, peel, and skin represent 31% of raw material used for this purpose and 36% is represented by stem, stalk, and straw. For example, biomaterials, such as carbon particles and biochar, which also serve as bio-adsorbents, have been obtained from garlic waste. different biomaterials, including an aerogel with cellulose nanoparticles (CNP), are proposed from husks, peels, and skins (26). Garlic residual biomass has also been reported as a precursor carbon electro-catalyst material (2). Additionally, using garlic skins, a film's microstructural properties have been improved for environmentally friendly dish creation (27), and cellulose nanofibre and nanoparticles have also been developed (56). Garlic waste has also been used to obtain a novel shape-stable phase-change material with garlic peels (47) and to prepare a cobalt-garlic peel nanocomposite (88). A study focused on generating eco-friendly biochar microparticles from garlic stalks and stems (table 1). Furthermore, garlic stems have produced low-cost and eco-friendly biochar microparticles (86).

Table 1 (page 220) illustrates that bio-adsorbent production from garlic waste is the

Table 1. Garlic waste valorisation as a biomaterial and bio-adsorbent.

Tabla 1. Valorización de los residuos del ajo como biomaterial y bio-absorbente.

Main use (Reference)		
Husk, peel, and skin 	Bio-adsorbent	To remediate
		Dyes (7, 49, 51, 57)
		Heavy metals, dyes, and antibiotics (76)
		Radioactive compounds (54)
		Antibiotics (89)
		Heavy metals (91)
		No specified (62)
	Bio-material	To produce or synthesise
		Aerogels (26)
		Films (27)
		Carbon particles or biochar (2, 18, 29, 43, 45, 46)
		Composites (47, 88)
		Nanoparticles (56)
		Nanofibre (87)
Stalk and stem 	Bio-adsorbent	To remediate
		Heavy metals (61)
		Dyes (35)
	Bio-material	To produce or synthesize
		Carbon particles or biochar (50, 63, 86)

second most investigated value-added product. Garlic husks, peels, and skins have been reused mainly as bio-adsorbents of the dyes cationic blue 41, methylene blue, and Direct Red 12B (7, 49, 51). Additionally, garlic stalks or stems have been revalorised as bio-adsorbents of methylene blue dye (37).

Other applications of garlic husks and stems are related to removing heavy metals and even pollutants as radioactive compounds from soil and water (54, 61, 62, 91). This last use has not been studied as extensively as dye remediation. Additionally, they have been used to absorb antibiotics such as Rhodamine B (76, 89). The effectiveness of garlic by-products bio-adsorbents and contaminants removers is due to garlic residual biomass high content of cellulose hemicellulose content, and some pectic components, which hydroxyl and carboxyl groups bound to pollutant molecules to remove them (57).

As mentioned in the previous lines, garlic residual biomass has been commonly used in the last years as a precursor to produce carbon materials or biochar for different applications (18, 29, 43, 45, 46, 50, 63). Biochar results from burning agricultural biomass organic material as an adsorbent, insulant, and carbon electrode to store energy, packaging, and pollutant treatment in air and water remediation (72). That means garlic husks and stems have suitable properties for reinforcement ingredients given their lignocellulosic composition, which is also natural, renewable, and biodegradable (68).

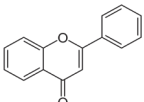
Bioactive compounds and biopolymers extraction

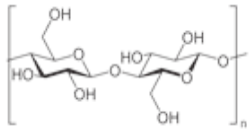
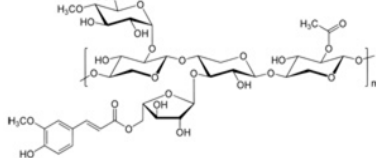
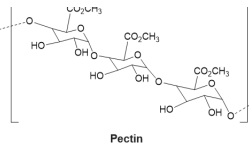
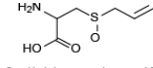
From ancient years garlic has been known for its medicinal properties. These properties are attributed to phytochemicals such as organosulfur compounds, phenolic compounds, and polymers (inulin and pectin), among others (13, 59, 70, 85). Figure 3 (page 219), depicts that 7% of related studies are focused on the valorisation of bioactive compounds found in wastes. These works are about different extraction processes, phytochemical activities evaluation, and food additive production from bioactive compounds. Table 2 summarizes articles about each chemical bioactive group mentioned.

As a result of the bibliographic search, the words aimed at biopolymers reached 7%

Table 2. Valorisation of garlic wastes to obtain bio-compounds and biopolymers.

Tabla 2. Valorización de residuos del ajo para la obtención de biocompuestos y biopolímeros.

Compounds of interest	Study [Reference]
Total phenolic compounds (TPC) and polyphenols  Phenolic compounds (PC)	Investigation of antioxidant and antimicrobial properties of garlic peel extract (<i>Allium sativum</i>) and its use as a natural food additive in cooked beef (32).
	Garlic (<i>Allium sativum</i> L.) husk waste as a potential source of phenolic compounds: Influence of extracting solvents on its antimicrobial and antioxidant properties (34).
	Extraction of phenolic compounds and antioxidant activity from garlic husk using carbon dioxide expanded ethanol (14).
	Evaluation of phytochemical activities of aqueous and ethanolic garlic peel extract (24).
	Comparison of the antioxidant activity of garlic cloves with garlic husk and stem: determination of utilisation potential of garlic agricultural wastes (81).
	Garlic (<i>Allium sativum</i> L.) peel extracts: From industrial by-product to food additive (20).

Compounds of interest	Study [Reference]
Polymers 	Starch-based bio-composite films reinforced with cellulose nanocrystals from garlic stalks (1).
	Isolation and characterization of cellulose nanocrystals from garlic skin (66).
	Polysaccharide from garlic straw: Extraction, structural data, biological properties and application to beef meat preservation (35).
	Isolation and structural characterization of cellulose nanocrystals extracted from garlic straw residues (36).
	Extraction and Characterization of Cellulose Microfibres from Agricultural Wastes of Onion and Garlic (67).
	Structure and morphology of cellulose fibres in garlic skin (64).
Dietary fibre 	Modification of insoluble dietary fibre from garlic straw with ultrasonic treatment (30).
	Antioxidant and physicochemical properties of soluble dietary fibre from garlic straw as treated by energy-gathered ultrasound (31).
	Determination of nutritional and mineral composition of wasted peels from garlic, onion, and potato (90).
Pectin 	Garlic peel derived high-capacity hierarchical N-doped porous carbon anode for sodium/lithium-ion cell (74).
	Effect of garlic peel on haematological, biochemical, and digestive enzyme activity in beluga juvenile (<i>Huso huso</i>) (15).
	Pectin extraction from garlic waste under dual acid condition (75).
	Synthesis and characterisation of edible films from garlic (<i>Allium sativum</i>) husk components (42).
Organosulfur compounds (OSC)  S-allyl-L-cysteine sulfoxide (alliin)	Comparison of two extraction methods (high-pressure extraction vs. maceration) for the total and relative amount of hydrophilic and lipophilic organosulfur compounds in garlic cloves and stems. An application to the Italian ecotype "Aglia Rosso di Sulmona" (23).
	Nematocidal effects of extracts of garlic, grape pomace and olive mill waste, on <i>Meloidogyne incognita</i> , on grapevine cv Chardonnay (53).

for husk, peel, skin waste, stem, stalk, and straw waste. Garlic macro components are water, carbohydrates, proteins, fibres, some fats and polysaccharides (3), including biopolymers which have been poorly analysed. These components also contribute to the specific organoleptic characteristics, as well as the medicinal and nutritional properties of garlic (33). All these characteristics make garlic and its by-products a special raw material to use as a functional ingredient (4). Figure 4, schematizes the bio-compounds and highlights the main obtention source from garlic residual biomass.

Other studies have addressed different *Alliaceae* wastes in terms of their extract's

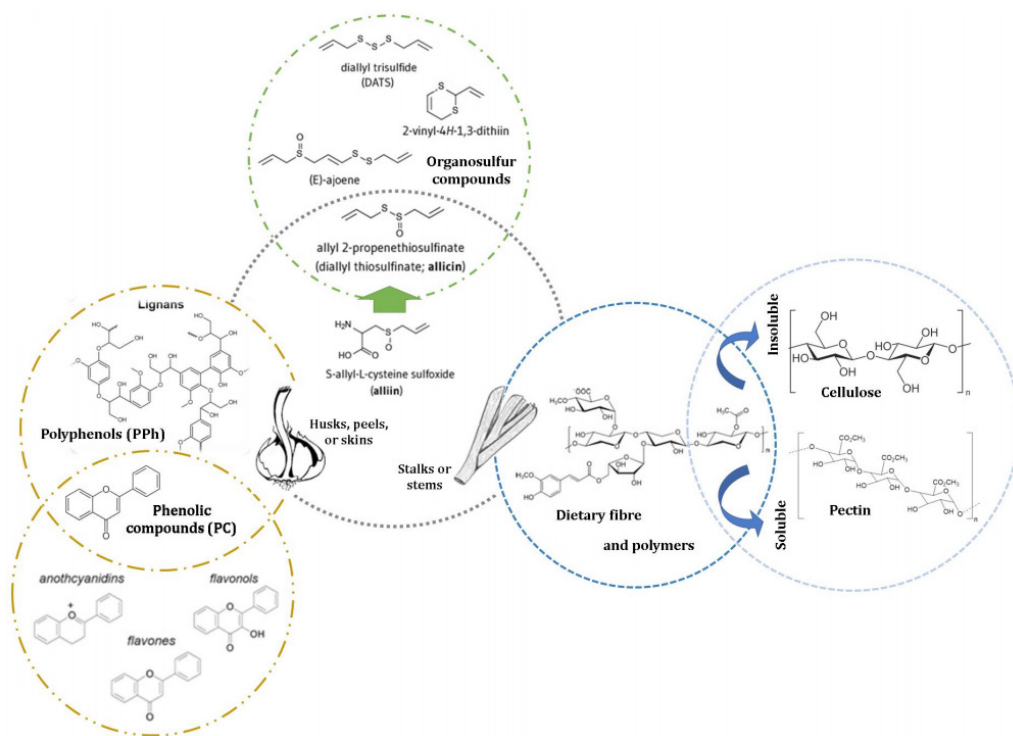


Figure 4. Bioactive compounds and biopolymers extracted from garlic husks and stalks wastes.

Figura 4. Compuestos bioactivos y biopolímeros extraídos catáfilas (piel) y tallos residuales del ajo.

bioactivity and composition (41, 58, 60). These studies provide critical information to support the upcycling of products like phytotherapeutics and food supplements. They also show that garlic stems/straws or husks/peels by-products have potential uses given their composition in bio-compounds and underline their diverse bioactivities.

Bioactive compounds

Phenolic compounds

Several garlic by-product extracts have been designed and obtained due to their phenolic compounds' antimicrobial, anti-inflammatory, and antioxidant activities (table 2, page 221-222). Likewise, in 2014, a study analysed polyphenols extraction from garlic husks using five different hydroalcoholic solvents, demonstrating their antioxidant and antimicrobial activity (34). Ifesan *et al.* (2014) evaluated garlic peel crude ethanolic extract, measuring its TPC content and antioxidant activity. The authors showed the effects on lipid peroxidation and microbial growth, proving garlic peel's potential use as a natural food additive.

Recent studies have focused on improving the extraction techniques to obtain phenolic

compounds. For this purpose, Chhouk *et al.* (2017) tested a new extraction method using supercritical fluids with carbon dioxide-expanded ethanol, measuring these extracts' antibiotic and antioxidant properties. Fortunata *et al.* (2019) tried to obtain diverse bio-compounds from garlic peels through aqueous and alcoholic extractions by comparing the phytochemical profiles obtained. Besides, Tahmas Kahyaoğlu (2021) evaluated the ethanol extract from garlic cloves, husk, and stem using an ultrasonic bath, evaluating their TPC content, total flavonoid, and antioxidant activity. Finally, dos Santos *et al.* (2022) used garlic peel as a co-product to extract bio-compounds by maceration and turbolisation. In the study, the crushed biomass was incorporated into the solvent (water and hydroalcoholic solutions) using a blender, evaluating the bioactive compounds and their bio-activities.

The previous reports illustrate garlic waste hydro-alcoholic extracts with applications in nutraceutical, medicinal, and pharmacological fields. According to the extractant, these investigations exhibit different alternative methods to obtain a wide range of polyphenols. They also show potential uses as antioxidants and antimicrobial activities against diverse pathogenic diseases as an alternative response to the current bacteria drug multi-resistant problem.

Organosulfur Compounds (OSC)

Despite the increasing interest in evaluating and finding new uses for garlic wastes to obtain bio-compounds such as OSCs, few investigations have addressed this aim. Of the total literature consulted, only one reported an extraction method to isolate OSCs from garlic straws. However, a similar task using garlic peels or husks was not reported (table 2, page 221-222). It is crucial to underline the need for further research on unexplored biopolymers and the possible novel extraction techniques and the new biological activity assay alternatives derived from this, mainly highlighting biocidal properties. In this way, Ferioli *et al.* (2020) evaluated two extraction methods, using different solvents to identify the total OSCs and their relative amounts in garlic clove and stem extracts. They detected the highest OSCs amounts in garlic cloves. Another study by Martinotti *et al.* (2016) evaluated the nematocide effect against *Meloidogyne incognita*, employing aqueous extracts from garlic bulbils with promising results.

Biopolymers

Cellulose extraction

The most common polymer extracted from garlic husks and straws is cellulose. Agustin *et al.* (2013) obtained cellulose from garlic stalks through chemical hydrolysis and sonication, obtaining nanocrystals, which were applied to produce a bio-composite film with starch. Another investigation obtained microfibre and nanocrystal celluloses from garlic skins by chemical hydrolysis, characterising the polymers by FT-IR, TGA, SEM, XRD, and SEM physical methods (66). A similar and recent study focused on the obtention of nanocellulose crystal, but in this case from garlic straw residues. The polymer was also extracted by chemical hydrolysis and characterised by the same analytical techniques (36). Likewise, garlic stalks and skins were treated to determine their chemical composition and obtain micro-cellulose fibres by alkaline hydrolysis. After a chlorite blanched process, the micro-cellulose fibres were characterised by FT-IR, TGA, and SEM physical assays (67). Similarly, Raimo (2020) studied a garlic skin extract's cellulose structure and morphology without any use or valorisation, evaluating it by microscopic and optical assays. Finally, a similar and recent study focused on the obtention of nanofibre cellulose, but in this case by a hydrothermal extraction pre-treatment (87).

In some studies, garlic husks and stalks were mainly evaluated to obtain different kinds of cellulose given the amount of this polymer in the residual material, which shows a novel source of cellulose fibres. For example, garlic straw contains 41% cellulose (36), garlic husk cellulose content reaches 19% (8). The biopolymer extracted/modified depicted important value-added characteristics, like tensile strength, moisture resistance, and thermal stability (68). Garlic husks and stalks are a potential bioresource with important technological applications in polymer matrices. They can be used mainly as a biodegradable film, to obtain bio-composites, or in food packaging production, being an eco-friendly material. This potential for circular economy practices is inspiring for the future of agricultural waste management.

Garlic wastes dietary fibre

Dietary fibre refers to non-digestible carbohydrates, including “resistant starch” and non-starch polysaccharides, cellulose, and pectin, among others. Generally, it is extracted by different hydrolysis methods using both acid and alkaline solutions. These fibres are usually used to produce dietary supplements due to their health benefits such as improving gut mobility, microbiota profile, facilitating weight loss, and reducing insulin sensitivity (9). Recently, few works have reported the soluble and insoluble dietary fibre content in garlic husks and straws (table 2, page 221-222). Of these, just one referenced garlic peel waste composition, in which dietary fibre was the highest part of the total residual biomass weight representing almost 62% (90). Huang *et al.* (2018) achieved to modify the functional, physicochemical, and structural characteristics of insoluble dietary fibre from garlic straw. Then, the same authors published that is possible to alter soluble dietary fibre from garlic straw with an energy-gathered ultrasound treatment (31). They provided information on the physicochemical characteristics and antioxidant capacity of the modified garlic straw dietary fibre. The most common research applied to garlic wastes (husks and straws) considers polymer obtention, mainly cellulose. Herein, Kallel *et al.* (2015) studied the isolation from garlic straws of a new polysaccharide mainly composed of glucose, mannose, galactose, and xylose. The polysaccharide was extracted in hot water, and its antimicrobial and antioxidant activities and structural conformation were assessed. According to the previous information, focus should consider these by-products reusing, given the fibre dietary content accessible and easily modified by conventional methods.

Pectin

It is interesting to explore the extraction of pectin from garlic by-products. It has been demonstrated that pectin extraction can allow differences in the esterification and methylation degrees, even in galacturonic acid content (75). These parameters influence the jell formation capacity of the extracted pectin (10).

Some previous pectin investigations from garlic peels have been retaken reporting it as a component of garlic peels constituting 27% of its biomass (15, 74). Similar data was described in a recent investigation that evaluated the pectin composition from garlic waste (peel, stem, and straw), reporting a pectin content of 22.4% (75). Thus, Kumar *et al.* (2022) synthesized and characterized different edible films from pectin garlic husk, demonstrating the potential of this biomass for making food packaging. The investigations in animal feeding have evaluated haematological and biochemistry parameters as digestive enzymes in fishes. The research demonstrated health benefits when the fish diet was supplemented with garlic peels, given to pectin content (15).

Despite these previous investigations, few findings have demonstrated that garlic peels are an important source of biopolymers focusing on its pectin content and functional potential. One of these emphasised the functional properties of the dietary fibre pectin in animal feed (table 2, page 221-222). It is important to further investigate other specific characteristics of the extracted pectin. Likewise, to know pectin-specific rheological properties and establish its potential uses as a nutraceutical assigning it a technological application in the food industry.

Current advancements and future trends

Though the circular economy has several practices for reducing environmental damage and the carbon dioxide footprint, residual biomass re-utilisation is the most extended practice. Thus, agro-industrial reuse of wastes or by-products involves reintegrating them into the productive system as raw material and removing value-added products useful for other production chains. Therefore, the productive systems must integrate into other practices if they want a circular economy-producing approach. These practices include repairing, reassembling, renovation, and upcycling proposed to incorporate by-products in new productive chains. Besides, a circular economy strategy helps to close the productive chain by obtaining bio-products and bio-energy from agro-industrial by-products. Some projects have been planned to produce garlic sustainability in Argentina. Burba *et al.* (2021) established a cleaner garlic production process by adopting some strategies. These include transforming tonnes of residual biomass into fuel pellets for heat locations and reusing

wood pallets, cardboard, and residual plastics such as raw materials to produce new packaging. These strategies should be integrated into other industrial and territorial organisation approaches and the garlic sector's Good Farming Practices (GFP). Nevertheless, the planned project does not consider bio-products from this garlic residual biomass.

Several studies support the idea that waste valorisation is a current point of discussion and a circular economy strategy using conventional techniques such as composting, digestion, or biotransformation is a possible way to do it. Upcycling is a recent innovative technique to obtain biofuel and bio-compounds and produce microbial growth media (17, 44, 71, 82). In this way, the revision of literature concerning garlic by-products shows the potential of obtaining bio-polymers and bio-compounds for bio-energy and bio-products generation. The final purpose of this review is to examine the links in the garlic production chain as sources of inputs from which new chains could be integrated to obtain additional by-products, thereby enhancing added value.

CONCLUSIONS

In summary, the present work analyses the state-of-the-art of garlic by-product valorisation. We identified references regarding garlic husk and straw valorisation as raw materials for obtaining different extracts and polymers, even energy or biofuels. Nevertheless, some current disposal practices of this biomass contribute to environmental damage. As an upcycling strategy, this raw material could be reused in production systems to exploit garlic by-products' physicochemical characteristics. Their reuse can diversify the number of bio-products obtained from them. Knowing that garlic is the second bulb worldwide distributed, and its consumption and processing have increased by-product generation. There is a need to deepen studies that contemplate waste treatment in considering circular economy. Fortunately, some investigations have focused on garlic by-product valorisation in recent years. Either extracting different bioactive compounds or seeking other ways to process it as a strategy for agro-industrial waste reduction.

This review evidences that the valorisation of garlic by-products can be divided into two clusters: the production of biomaterials and the extraction of bioactive compounds. These works highlight the advantages of reusing a discarded material such as a low-cost natural source of easy accessibility to be applied at an industry level. Since garlic husks and straws represent almost 10% of the total weight of garlic, reducing their amount of worldwide solid waste could be a trending topic. Nevertheless, using this raw material in other value chains for obtaining bio-products and bio-energy, still represents a major underexplored topic. Bio-compound isolation is another relevant aim in residual garlic biomass revalorisation, and it demonstrates its potential applications in the nutraceutical, medicinal, and pharmacological fields. Though there is increasing interest in evaluating and finding new uses and valorisation of garlic wastes, their upcycling is scarce. More deep studies focused on garlic peels and straws, as an important source of other unexplored biopolymers and phytochemicals in this complex matrix, should be addressed. Therefore, investigating new substances from garlic peels and straws will improve the extractive techniques as the structural characterisation and the biological screening assays. The discovery of new evidence to revalorise this raw discarded material in diverse technological applications must consider the SDGs and circular economy approaches.

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