Review

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Sustainable Waste Management in the Production of Medicinal and Aromatic Plants – A Systematic Review

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Review

Sustainable Waste Management in the Production of Medicinal and Aromatic Plants—A Systematic Review

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Abstract: Due to the growing demand for Medicinal and Aromatic Plants (PAMs), environmental risks associated with overexploitation and inadequate waste management are increasing. Since MAPs residues have a notable potential to be valorised, the implementation of Circular Economy solutions can play a central role in transforming waste management problems into economic opportunities and in responding to the growing demand for MAPs. Circular economy is viewed as a solution for fostering a sustainable system planet and positively contributes to the economy and society. A systematic review was conducted aiming to identify potential applications for the valorisation of MAP, under a sustainable waste management and circular economy approach. A total number of 47 studies were analysed and it was verified that MAPs residues can be valorised for energy purposes, crop management and applications in chemical, food, pharmaceutical, cosmetic industries, among others. Despite the wide range of possible applications, to promote a progressive implementation of circular economy strategies by the industry, further investigation is needed regarding the development of more efficient techniques and technology to develop value-added products and the assessment of sustainable performance in empirical investigations, considering both economic and environmental indicators.

Keywords: medicinal and aromatic plants; sustainability; circular economy; waste management; valorisation

1. Introduction

The Medicinal Plant Specialist Group of the International Union for Conservation of Nature (IUCN) provides the following definition for Medicinal and Aromatic Plants (MAPs): "Includes plants used to produce pharmaceuticals, dietary supplement products and natural health products, beauty aids, cosmetics, and personal care products, as well as some products marketed in the culinary/food sector" [1].

There is evidence about the growing inclination towards natural plant-derived products, and 11% of the basic drugs considered by the World Health Organisation (WHO) are exclusively of plant origin [2].

Moreover, According to data from The International Trade Centre (ITC), the world trade of MAPs resources is growing at the rate of 10–12% annually [3]. With the rising demand for MAP, the risk of overexploitation increases [4].

Almost two decades ago natural resources were already rapidly diminishing. The loss of plant species was recently estimated to be between 100 and 1000 times higher than the expected extinction rate due to natural causes [5].

Overexploitation can generate changes in the structures and population dynamics patterns of extracted species. Once overexploitation affects plants growth and reproductive capacity [6], it may even lead to the loss of existing populations [7].

However, MAPs overharvesting does not only generate harmful effects for these individual species. It can also adversely affect the wildlife population and result in the loss of multiple ecosystem services [4].

Furthermore, along with the increasing in the world trade of MAP, it also increases the waste generated in the industry.

It is estimated that every year the medicinal herb industry generates about 30 million tons of waste [8]. In spite of containing nutrients and/or bioactive substances, the massive herb residues have been directly disposed through stacking, landfill or burning, which not only is a waste of resources, but also causes considerable environmental pollution [9].

Most part of waste biomass from agro-industry is deposited in landfills or simply discarded in inadequate places. The biomass accumulation contributes to fires in regions with a drier climate, leading to large losses of forests and biomes. It also promotes the proliferation of microorganisms, which despite being important for decomposition, on a large scale become a major problem, mainly associated with the production of greenhouse gases, toxic degradation products, and proliferation of pathogenic microorganisms.

On the other hand, when agro-industrial wastes are incinerated, the production of greenhouse gases increases, contributing to the loss of energy potential, worsening health crises and affecting the population's quality of life [10].

While conventional waste management is driven by minimizing the costs of collection and disposal, Circular Economy aims to maximize value at each point in a product's life [11].

Circular Economy can be defined as a "*regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops*" [12] (p.759)[12] . This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling [12].

Circular Economy can also be defined as the transition from a linear model, where resources are transformed, used, and discarded, to a circular (regenerative) model in which materials are reused whenever possible [13]. Circular Economy solutions are aligned with the UN Sustainable Development Goals requiring transformation of the current commercialization and economic business model [5].

Circular Economy is viewed as a solution for fostering a sustainable system [12] and aims for the elimination of waste [14]. Additionally, applying Circular Economy strategies can be beneficial not only for an economic gain, but it can also be a practical solution for the optimum use of biological resources, encouraging more viable and responsible sustainability strategies in the MAPs sector [2], [5].

Furthermore, through sustainable waste management approaches in agriculture, and particularly in MAPs production, it is possible to explore valuable natural resources generating economic value at a low environmental cost, without threatening the accessibility and availability of plants, as well as the general well-being of future generations [15].

Nevertheless, according to Taghouti *et al.*, [16] concerning the transformation and processing, the valorisation of the by-products obtained in the distillation and drying processes is one of the faced challenges by the MAPs sector [16].

In this study, a systematic review was conducted aiming to answer the following question: How can MAPs production residues be valorised, under a sustainable waste management and circular economy approach? It is also intended to clarify what are the sustainable benefits of waste valorisation applications.

This article starts with the description of the methods applied to extract the analysed literature. Section 3 presents descriptive and thematic results, describing the variety of waste valorisation for MAPs residues presented in literature and some positive effects associated. The discussion section explains the main findings, limitations and topics for future investigation and in conclusion the possible applications for MAPs residues are summarized.

2. Materials and Methods

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The systematic literature review was carried out following PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) guidelines, which were conceived to promote a transparent report of results [17]. The PRISMA methodology is divided into four stages: identification, screening, eligibility, and inclusion for analysis [18].

In April 2023, identification, i.e., data collection for this systematic review was performed. Three electronic databases were consulted, namely, Scopus, Web of Science and PubMed. For the database search the keywords presented in Table 1 were chosen. Since it was verified that using only one search equation significantly limited the number of results, four different search equations were used.

Table 1. Keywords and search results for the systematic literature review.

Search String	Database	Papers Found
TITLE-ABS-KEY ("circular economy" OR "circular farming" OR "circular agriculture") AND ("aromatic plant*" OR "medicinal plant*" OR "aromatic herb*" OR "medicinal herb*" OR "aromatic flower*" OR "medicinal flower*")	Scopus	21
	Web of Science	18
	PubMed	8
TITLE-ABS-KEY ("*waste* management" OR "*waste* valorization" OR "*waste* valorisation" OR "*waste* reuse" OR "*waste* recycling" OR "management of *waste*" OR "valorization of *waste*" OR "valorisation of *waste*" OR "reuse of *waste*" OR "recycling of *waste*") AND ("aromatic plant*" OR "medicinal plant*" OR "aromatic herb*" OR "medicinal herb*" OR "aromatic flower*" OR "medicinal flower*")	Scopus	59
	Web of Science	24
	PubMed	14
TITLE-ABS-KEY ("*residu* management" OR "*residu* valorization" OR "*residu* valorisation" OR "*residu* reuse" OR "*residu* recycling" OR "management of *residu*" OR "valorization of *residu*" OR "valorisation of *residu*" OR "reuse of *residu*" OR "recycling of *residu*") AND ("aromatic plant*" OR "medicinal plant*" OR "aromatic herb*" OR "medicinal herb*" OR "aromatic flower*" OR "medicinal flower*")	Scopus	4
	Web of Science	5
	PubMed	122
TITLE-ABS-KEY ("by-product* management" OR "by-product* valorization" OR "by-product* valorisation" OR "by-product* reuse" OR "by-product* recycling" OR "management of by-product*" OR "valorization of by-product*" OR "valorisation of by-product*" OR "reuse of by-product*" OR "recycling of by-product*") AND ("aromatic plant*" OR "medicinal plant*" OR "aromatic herb*" OR "medicinal herb*" OR "aromatic flower*" OR "medicinal flower*")	Scopus	3
	Web of Science	1
	PubMed	21
Total		300

The 300 articles initially obtained were manually screened based on the title and abstract reading. Articles were excluded if:

- There was a duplicate article in another database;
- The full text could not be accessed;
- They were not written in English;
- They were not related with MAPs;
- They did not refer circular economy or waste management concepts.
- In the eligibility phase, articles were excluded if:

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- They were not related with MAPs residues (Reason 1);
- They did not present potential applications to valorise MAPs residues (Reason 2).

A PRISMA flowchart illustrates the step-by-step process of the application of inclusion and exclusion criteria to generate a final number of studies for analysis [18]. Figure 1 was elaborated according to the PRISMA 2020 statement revised flow diagram [17].

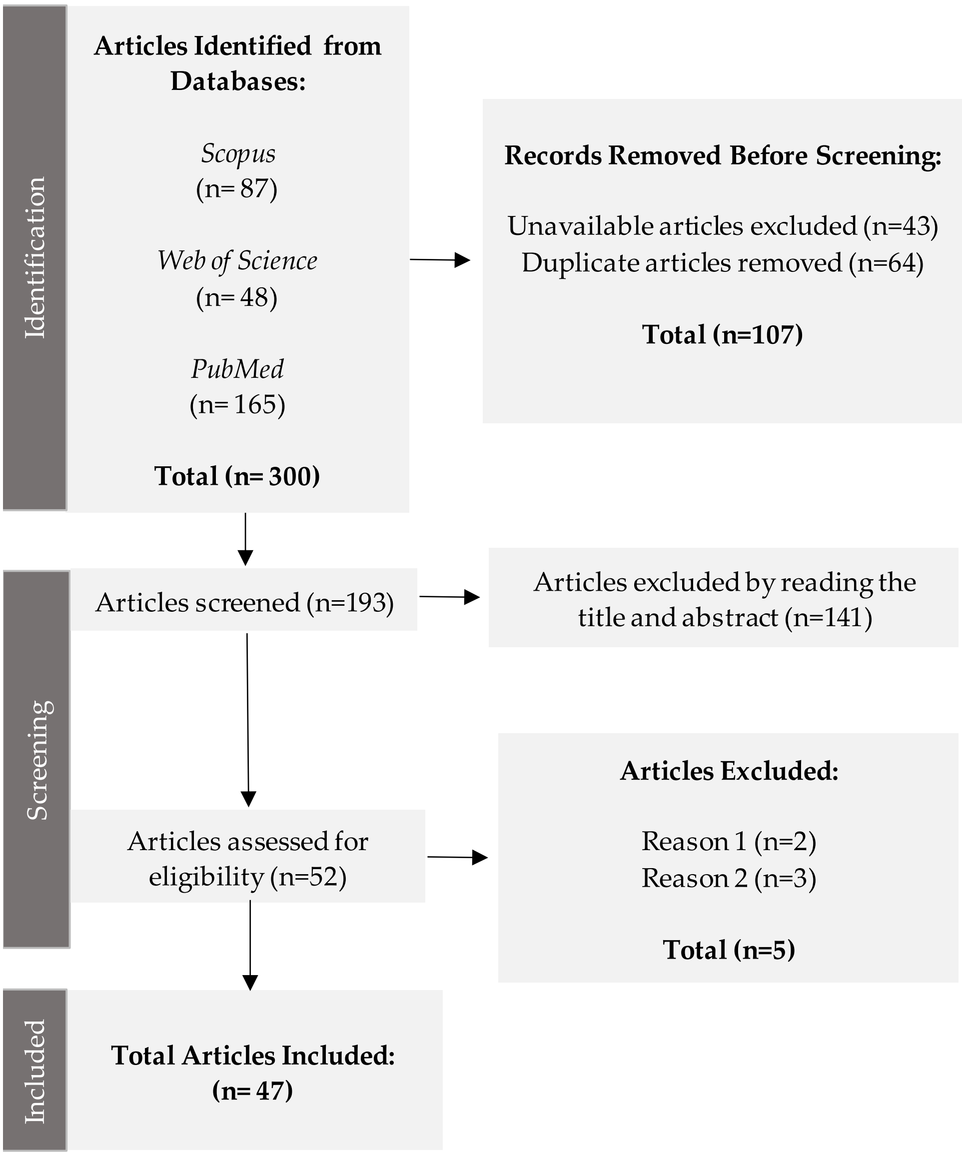

Figure 1. PRISMA flowchart.

3. Results

This section is divided in three subheadings. In the first one, descriptive results are presented and in the second one the results of the thematic analysis of the literature are described. The third subheading presents positive effects of waste valorisation applications.

3.1. Descriptive Results

The analysis of the extracted literature concerning the number of articles published by year allows to conclude that since 2019 until 2022 the number of published articles increased each year, which evidence the growing research interest in waste valorisation solutions for MAPs sector (Figure 2).

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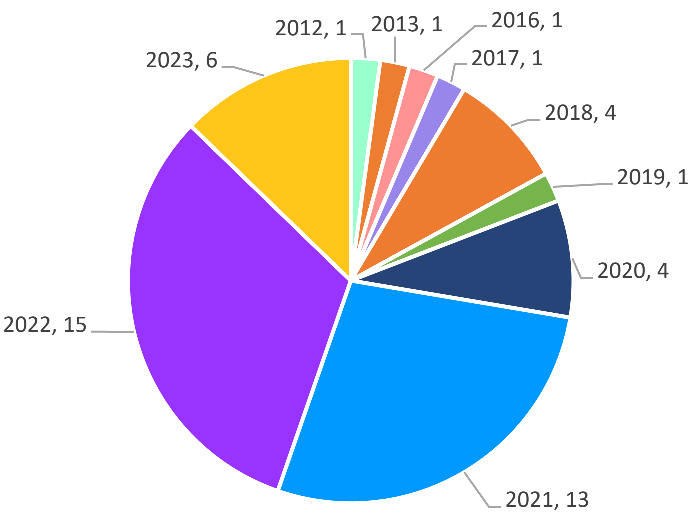

Figure 2. Number of articles published by year.

The locations shown in Figure 3 correspond to the location associated to the first author or the respective afilliation. It was verified that China is the country with the highest number of publications (10). This feature is congruent with the considerable use of plants in Traditional Chinese Medicine practices, and the consequent interest in an efficient use of these natural resources. After China, Italy, France and India are the countries with higher nummber of publications.

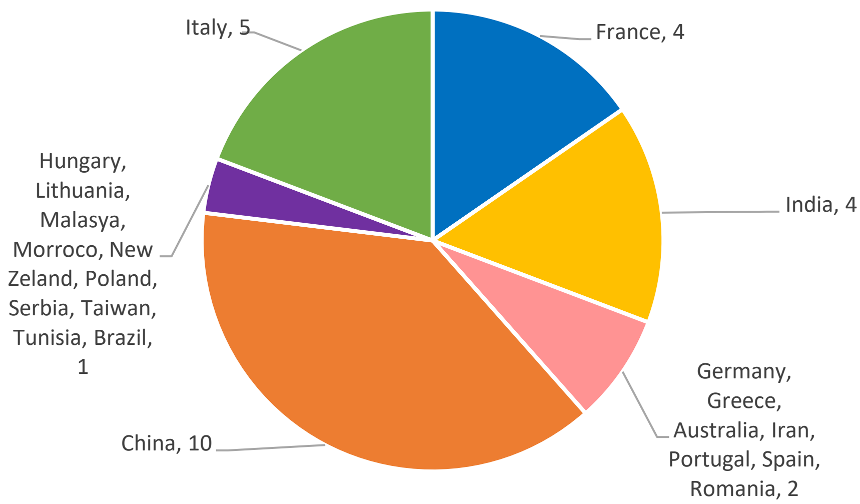

Figure 3. Number of articles published by location.

3.2. Thematic Results

The possible solutions to valorise MAPs residues, converting them in value-added goods, are presented in this subheading. These solutions comprehend energy purposes, crop management and applications in chemical, food, pharmaceutical and cosmetic industries, among others.

3.2.1. EnergyPurposes

Herb residues can be converted into gas fuel to provide energy for productive systems. For instance, Guo *et al.*[19] proposes using the heat of the flue gas from a boiler in herb residues drying in order to recycle energy and designs a utilization mode for industrial-scale utilization of herb residues by gasification.

Plant solid residues obtained from hydrodistillation process can be used to produce energy through direct burning, making briquettes after drying, pelletizing and gasification. Indirectly, these residues can be used in biomethanization and pyrolysis processes, to obtain biodiesel and biochar for energy purposes [21, 22].

According to Robertson *et al.* [22], cannabis waste, including cannabis biomass, solvents, packaging and unused product, can be used for incineration, which consists in the combustion of waste in a furnace with the intention of reclaiming energy exposed from the process and reducing the volume and mass of waste generated.

Beyond landfilling, composting and incineration, cannabis waste can be used for anaerobic digestion. Anaerobic digestion is similar to composting, where anaerobic microorganisms digest the waste in the absence of oxygen and generates a digestate and biogas. The produced biogas can be used for sustainable energy production and predominantly consists of methane [22].

Fardad *et al.* [23] present the results from mesophilic anaerobic digestion of Glycyrrhiza Glabra Waste (GGW), Mentha Waste (MW), Cuminum Cyminum Waste (CCW), Lavender Waste (LW) and Arctium Waste (AW). The study concludes that the anaerobic digestion of these wastes seems a very promising option for integrated solid waste management systems. These residues allow to produce biogas and to recover methane as a source of renewable energy, instead of burning or burying them [23].

3.2.2. Crop Management

MAPs by-products may be rich sources of bioactive compounds and beneficial microorganisms. Therefore, they can be used as natural biopesticides or organic fertilisers, which may suppress the growth of major soil-borne phytopathogens [24].

Under a circular economy approach, the use of these residues is also recommended to the restoration of degraded and marginal lands [20].

Through composting and vermicomposting technologies, these by-products can be used to improve important soil processes and provide nutrients for the treated crops [24].

Composting has become the most important way to recycle medicinal herbal residues [25] and it is a sustainable approach for dealing with organic waste by converting them into stabilised soil amendments and horticultural growth media using decomposing organisms under aerobic conditions [22].

Zaccardelli *et al.* [21] demonstrated that it is possible to valorise all fresh aromatic plant residues, composting being one of the applied techniques. The study used residues from cropping and processing stages, such as the whole basil plants at the end of the cycle, the pruning residues from rosemary and all the pre-packaging green waste of basil, rosemary, and sage, including leaves, stems and inflorescences.

Zaccardelli *et al.* [21] stated that oil-free biomasses from the harvesting, production and processing of MAPs are suitable for use in agriculture for composting and to obtain a high-quality organic fertilizer. The same study assessed the reuse of the remaining residues.

The fresh biomass of aromatic residues was cut into small pieces, and, through hydrodistillation, it was used to recover essential oils. All the positive characteristics of the specific aromatic plants considered in the study were present in the recovered essential oil, despite not being collected in their balsamic stage [21].

The study also concluded that the aromatic waters recovered at the end of the steam distillation of these plants are a product that is easy to use, as they have the characteristic aroma of the species, emphasizing the high antioxidant activity of basil [21]. Therefore, the combination of different techniques, including composting, can enable the valuation of all fresh plant residues, under Circular Economy principles.

Solid residues from distillation also exhibited the capacity to stimulate seed growth [26].

Regarding the use of antibiotic-contaminated swine manure in agriculture, the study of Zhang *et al.* [27] suggest that anaerobic co-digestion with chinese medicinal herbal residues could be employed to remove some antibiotic resistance genes (considered emerging pollutants with risk to the environment and human health) and mobile genetic elements from swine manure.

Like composting, the process of anaerobic digestion, using herb residues, generates a digestate high in minerals and nutrients for plant growth, allowing it to be used as a fertiliser [22].

The study of L. Wei *et al.* [28] used traditional Chinese medicinal herb residue to produce biochar adsorbent by pyrolysis. The use of biochar as a soil amendment can enhance soil productivity, mitigate climate change and it is also indicated as a sorbent for immobilization of potentially toxic elements, and organic contaminants not only in the soil, water and air [28].

B.B. Basak *et al.* [29] describes a novel biochar-mineral-complex, which was prepared using a biochar derived from distillation waste of Lemongrass (*Cymbopogon flexuosus*). The study found that the biochar-mineral-complex improved the soil quality by enhancing available nutrients and biological activities. Thus, the use of waste of Lemongrass can be incorporated in biochar-mineral-complex formulations to produce an excellent starter fertilizer, and a potential alternative of chemical fertilizers [2].

Regarding the effectiveness of herb residues as organic fertilizers, the study of J. Ma *et al.* [30] revealed that Chinese medicinal herbal residues can replace 25–50% of the amount of chemical fertilizer normally applied to fields without hampering maize grain yields. Such application to agricultural fields is an effective recycling strategy and nutrient management practice to improve soil fertility and reduce chemical fertilizers usage [30].

Additionally, the research performed by V. Filipović *et al.* [31] confirmed that using compost from organic waste, obtained in the processing of medicinal plants, on marigold improved the productive and qualitative traits of plants as if they were fertilized with commercial fertilizer. The results suggest that MAPs waste can be applied as an alternative to other organic and conventional fertilizers [31].

Using aromatic plant waste biomass to obtain effective soil amendments (e.g., compost and biochar) might not only mitigate greenhouse gases, and at least partially replace chemical fertilizers. Furthermore, the application of biochar and improves the physical, chemical, and biological qualities of agricultural soils, supplying and retaining nutrients [2].

A study about the suitability of *Salvia sclarea L.* (sage) and *Coriandrum sativum L.* (coriander), combined with an arbuscular mycorrhizal fungus inoculant, to immobilize metal(-loid)s and produce essential oils (EO) in a contaminated land, concluded that the metal concentrations in the sage essential oil were similar to those obtained from plants cultivated on an uncontaminated soil. Since sage presents an excluder phenotype, its use is suitable for phytostabilisation, and the residues of oil extraction could be used as a soil conditioner. On the other hand, the use of distillation residues of coriander was limited by their relatively elevated Cd concentrations [32].

The study by Fontaine *et al.* [33] also indicates that, although *C. sativum* is useful for phytomanagement of polluted soils by trace elements, the valorisation of its distillation residues are limited since it is a Cd accumulator, being Cd recognized as one of the most hazardous pollutants due to its severe toxicity and high mobility in soil.

Beyond all the previous mentioned possible uses for residues from MAPs production, solid residues from distillation can also be used as biosorbents, as soil organic cover or to weed management. Also, the hydrolates can offer a source of active compounds that can be profitably used to make eco-friendly biopesticides [21], [26].

3.2.3. Chemical Industry

MAPs biomass can also be a raw feedstock for green chemistry industry. For instance, Kong *et al.* [9] proposes the recycling of Chinese herb residues by endophytic and probiotic fungus *Aspergillus cristatus* CB10002 for the production of anthraquinones, an important chemical compound with a wide range of medicinal activities.

MAPs residues can also be applied to enzyme synthesis. Through delignified bio-processing of residual biomass of MAPs, such as Java citronella (Cymbo-pogon winterianus) and Artemisia annua (known as marc of Artemisia), it is possible to produce cellulase enzymes [2].

Also, the study by Lesage-Meessen *et al.* [34] demonstrated that the distilled straws of lavender and lavandin are cheap and readily available industrial by-products of interest for producing platform molecules (e.g. antioxidants) and fungal enzymes involved in the degradation of lignocellulosic biomass.

These approaches could represent sustainable strategies to obtain high-added value compounds, while fostering the development of circular bioeconomy [34].

3.2.4. Food Industry

Agri-food by-products, including MAP, can be exploited by the food industry as natural sources of functional ingredients for animal feed or human consumption due to their high nutritional value and rich content of bioactive compounds with beneficial properties [35].

Some of the residues generated in medicinal herb industry, especially from ethanol or water extraction, can be used as feed additive in animal husbandry, since they still contain 30–50% essential bioactive compounds [8].

A review article about the application of medicinal herbs in aquaculture revealed that current probiotic and medicinal herb combinations as a feed additive can benefit aquaculture industry by boosting the aquaculture species' growth performance, immune system, and disease resistance. [8]

Andreadis *et al.* [35] conducted a study about the use of post-distillation residues, of Mediterranean MAP, namely lavender, Greek oregano, rosemary and olive (1:1:1:1 ratio), in substrate supplementation with rice bran, corncob, potato peels, solid biogas residues and olive-oil processing residuals.

The results showed that MAPs residues had an apparent favourable impact on total phenolic content and antioxidant activity of each substrate, with rice bran displaying the highest capacity and content. These findings indicate that alternative substrates can be exploited and their enrichment with natural phenolics is able to influence T. molitor (an important commercial edible insect especially valued for its protein content) growth, offering highly beneficial and nutritional value.

Moreover, solid residues from MAPs hydrodistillation can be considered as a low-cost deodorized material, free of volatile compounds. Since odorous ingredients can impair the organoleptic properties of the product, or result in rejection problems when used in animal feed, these solid residues have a useful potential in the food industry, in both animal feed and food supplement [26].

For instance, the solid residue from rosemary (*R. officinalis*) has potential to be used as an antioxidant feed supplement for pregnant ewes to reduce lipid oxidation of meats. This solid residue is even considered by the European Commission as a semi-natural additive for the preservation of food (as regulated in the code E-392) [26].

The use of ethanol extracts from the solid residues of Lavender (*Lavandula angustifolia*) and Lemongrass (*Melissa officinalis*) is also suggested to extend the shelf life of bread [26].

Also, extracts of residual water (i.e., the water that was in contact with the aromatic plant during distillation) can be applied as nutraceutical, functional food additives and food antioxidants [26].

Antioxidant properties are desired not only in medicinal and cosmetic applications, but also in the food sector, since many processed products require the addition of stabilizing, colouring or preserving ingredients. Due to the growing interest in natural formulations without synthetic additives, plant extracts are increasingly incorporated as natural antioxidant compounds in food industry [36]

Furthermore, the study by Dobravalskyte *et al*. [37] affirms that in some cases deodorised plant extracts produced from the essential oil free material were reported as possessing higher antioxidant power than the extracts isolated from the whole material. Therefore, since some MAPs residues exhibit significant antioxidant activity, there is potential to increase their use in the food sector.

3.2.5. Pharmaceutical and Cosmetic Industry

The guidelines of the European Commission validate the reuse of various types of organic biomass and organic waste [38]. The growing demand for bioactive compounds from MAPs for pharmaceutical and cosmetic applications promotes the development of sustainable methods to increase the effectiveness of new active formulations [38].

An efficient valorisation of MAPs residues must consider, whenever possible, all their valuable properties and choose applications accordingly.

If herb residues still contain nutritional and medicinal ingredients, approaches such as pyrolysis or gasification to obtain fuel gas, or conversion into biochar, among others, ignore the effective potential of materials and, usually, are high energy consuming, which are not beneficial for green and practical applications [9].

The solid residues, i.e., the oil-exhausted biomass obtained after the extraction of essential oils are mainly used for mulching in other crop cultivations or for energy production from combustion. Still, such residues are rich in polyphenols which are not volatile and thus not collected in the obtained essential oil [39].

Residues from distillation (solid residues, wastewater and hydrolates) of MAPs are known to be valuable sources of phenolic compounds of interest [35], such as terpenes, phenolic monoterpenes, phenolic diterpenes, hydroxybenzenes, phenylpropanoids, and flavonoids [26].

Flavonoids, which are present in some aromatic plant distillates, are involved in the prevention of photoaging damage. The potential beneficial dermatological effects provided by these phenolic compounds present in MAPs production residues may favour their application in modern medicine [38].

The study of Marzorati *et al.* [40] demonstrated the presence of relevant percentages of unextracted compounds from medicinal plants residues (*Cucurbita pepo* L. seeds and *Serenoa repens* L. fruits) such as fatty acids, sterols and polyprenols. Bioactive molecules from MAPs residues can be directly usable as phytotherapic drugs or combined as ingredients in specific pharmaceutical preparations [40].

As many active ingredients remain after decoction or extraction, re-extraction, is an attractive important and necessary method to efficiently increase the exploitation of MAPs properties, increasing their economic value, while reducing waste [41].

The study of Meng *et al.* [42] present another technique to valorise traditional chinese herb residues in health sector. It was concluded that herb residue fermentation supernatant successfully inhibited urease activity, reduce the level of some gastric inflammatory cytokines, alleviate histological lesions, and help to recover the disturbed microbiota to a normal level. This finding can lead to the development of new healthcare products [42].

Table 2 summarizes the residues reuse applications of specific MAPs species presented in the extracted literature, including phytochemical studies and review articles.

Table 2. Properties and potential applications for MAPs residues.

Plant Specie	Origin of Sample Materials	Waste Type	Properties	Application	Reference
Chamomile (*Matricaria recutita* L. and *Matricaria discoidea* DC)	German	Roots of flower production for tea	Middle polar extracts have bioactive phytochemicals, potent antioxidant, and antibacterial activity.	Phytomedicinal or cosmetic preparations (oil-based cosmetic products)	[36]
Argan (*Argania spinosa* L.)	South-Western Morocco	Shell fruit from argan oil production	Ethanol extract has high level of total phenol content, flavonoids, condensed tannins, and flavanol; has a potential antioxidant effect, potential anti-inflammatory, and antioxidant activities.	Pharmaceutical and food industries.	[48]
Calamintha grandiflora L.	South-west of France	Water extracts	Antioxidant activity and offers protection against oxidative deterioration.	Formulation of food additives, functional food components and healthy supplements	[37]
		Solid hydrodistill	Antioxidants and volatile aroma compounds.		

		ation residue			
Lotus (*Nelumbo nucifera* Gaertn.)	-	Lotus seedpods	Extracts have antioxidant, anti-cancer, anti-melanogenic, anti-inflammatory, anti-irradiation, cardioprotection and hepatoprotection bioactivities.	Health food industry and medicine	[46] *
			Water extracts exert antioxidation, anti-cancer, anti- melanogenic, anti-inflammatory and hepatoprotection activities.		
Lovage (*Levisticum officinale* W.D.J. Koch)	Spain	Dried Roots	Bioactive compounds, such as phthalides and phenolic acids.	Food and/or the pharmaceutical industry.	[49]
Mangaba (*Hancornia speciosa* Gomes, Apocynaceae)	North-east Brazil	Leaves	Extract rich in cyclitols and flavonoids and high amounts of bornesitol.	Development of antihypertensive herbal medicine or as source of the bioactive constituent bornesitol.	[13] *
Caryocar brasiliense A.St.-Hil., (Pequi)	North-east Brazil	Peels	Tannins, including corilagin and geraniin; antiviral properties.	Development of antidiabetic and antiviral herbal medicine.	[13] *

3.2.6. Further Apllications

This section presents additional MAPs waste management possibilities.

MAPs residues can be reused as raw material for paper-making [9] and in wood-based panel industry [43].

Following the principles of circular economy, Fehrmann *et al.* [43] suggests that residual hemp (*Cannabis sativa* L.) biomass, namely hemp hurd, can be used as an alternative, renewable lignocellulosic feedstock in the manufacture of engineered lightweight panel products. This strategy not only reduces waste production, but also allows to address the increasing resource scarcity in the wood-based panel industry [43].

Residual biomass of MAPs can be used as effective adsorbents for heavy metal and pigment removal and waste water treatment [2].

Huang *et al*. [41] carried out an investigation about bio-based materials production using traditional chinese medicinal herb residues. Using Radix bupleuri, astragalus roots, Radix liquiritiae, Fructus aurantii, Fructus gardeniae, Evodia rutaecarpa, Herba plantaginis, lobelia, and Cacumen platyclade (namely rhizomes, fruits, and leaves, being 5:4:2 the optimal ratio), it is possible to produce activated carbon for an efficient cephalosporin antibiotic adsorption in wastewater. Both cephalexin and cefradine with low concentration can be adsorbed, and the produced activated carbon can be reused for adsorption after ultrasonic treatment in water.

Additionally, chinese medicinal herb residues can be used for materials and chemicals production, namely composites synthesis. The composite generated from H. angustifolia root xylem and polylactic acid exhibit promising comprehensive mechanical properties [41].

Another study indicates that Magnolia (*Magnolia officinalis*) bark extract residues due to their Moisture and lignocellulosic contents can be used as raw material to prepare composites which can be moulded into products. It was found that the composites containing 20% MBER residue formed products with optimal impact and bending strengths both with and without soaking in water. [44]

The study of Ratiarisoa *et al*. [45] used raw lavender straw, a mix of stems, flowers and other degraded elements, to produce and evaluate a bioaggregate for building materials. It was concluded that, although further investigation is needed, distilled lavender straw can potentially be used to build bioaggregate, since the produced composite exhibited promising thermal and hygric performances. Nevertheless, lavender based composite exhibited very weak mechanical performances and further tests should be performed to optimize its performances for building applications.

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Thus, MAPs residues have the potential to be used in the production of paper, wood-based panel industry, composites synthesis, wastewater treatment, and in building materials.

3.3. Positive Effects of Waste Valorisation

Beyond the tangible benefits of waste valorisation from MAPs industry, there are sustainable benefits involving environmental, health and economic dimensions.

For example, when residue burning or direct application to the field is replaced by the production of biochar, the greenhouse gas (CO_2) emission is reduced. Moreover, tthe use of biochar was found to reduce the NO_2 emission from agricultural soils [2].

Applying MAPs residues as soil amendments reduces the energy consumption in the production of agro-chemicals and minimizes environmental and health implications associated with chemical fertilizers use in agriculture [2].

The valorisation of MAPs residues contributes to waste minimization, climate change mitigation, soil carbon sequestration, soil fixation, soil quality improvement, and provides a range of ecosystem services [20].

Under a circular economy approach, the organic waste of MAPs industry can be converted into economic opportunities.

The implementation of Circular Economy strategies can play a central role in transforming waste management problems into economic opportunities and in responding to the growing demand for bioactive compounds in the pharmaceutical and cosmetic industries [38].

The use of MAPs residues to create add-value products requires low-cost raw materials, which are also environmentally friendly, economically viable, and scalable to industrial use [44]. Also, if cheap value substrates, such as agricultural residues, are used in enzyme production, and other MAPs based products, production costs can be reduced and it would solve, to some extent, waste disposal problems in the industry [2].

4. Discussion

In this systematic review, we screened 193 journal articles and selected 47 articles which contained potential applications to valorise MAPs residues.

Existing reviews have focused, particularly, on distillation residues to recover phenolic compounds [26] and on the technology developed at laboratory scale and their application in industry to valorise residual biomass from MAPs [2]. Since the number of publications in this research field has been increasing, the more general and recent scope of this review allowed to identify recent findings.

First, as demonstrated by [31], MAPs processing waste has the potential to improve the production and quality of plants as if commercial fertilizer was used. Replace chemical fertilizer usage by organic soil amendments reduces soil nutrient loss, sustains crop yields, and protects the environment [30], while reducing residues in MAPs production.

However, future research about the use of MAPs residues as soil amendments is required to optimize the observed effects and to assess such application at field-scale level [33]. Also, it is relevant to perform empirical investigations about the effects of long-term application of MAPs residues on productivity, soil microorganisms, carbon storage and conversion, greenhouse gas emissions and enzyme activities in agricultural systems [30]. These effects should also be discussed in comparison with the ones associated with the long-term application of chemical fertilizers.

Second, although there are several studies about the potential for valorisation of MAPs residues, recent studies point to the need to evaluate the efficacy of phytomedicinal or cosmetic preparations [36] and identify more efficient methods to prepare phytochemicals that can be adapted to industrial scale [46] [47].

Third, a representative portion of the analysed literature presents phytochemical studies, suggesting that by-products from MAPs sector are a promising source of natural organic molecules for the development of innovative products in the field of biopesticides and biofertilizers, as well as in food, pharmaceutical and cosmetic industry. Therefore, there is a wide range of possibilities in

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investigation about product design and for nutraceutical and pharmaceutical innovation strategies using MAPs residues and assessment of their efficacy.

Four, even though some articles refer the positive effects of residue valorisation strategies to environmental sustainability, in the extracted literature for this systematic review, no studies were identified about an empirical evaluation of such effects.

Additionally, no studies were identified about economic feasibility assessment of MAPs residues valorisation. Despite MAPs residues having a great potential to be valorised, more studies about application in real cases are needed.

To promote a progressive implementation of circular economy strategies to valorise MAPs residues by the industry, further investigation is needed regarding:

- Identification of barriers and drivers for industrial implementation.
- Development of more efficient techniques and technology for the extraction of valuable compounds from MAPs residues and for their usage to develop value-added products for crop management.
- Development of a decision support system to assess the sustainable performance considering economic, environmental, and social indicators, of both new and existing businesses based on MAPs residues valorisation.

5. Conclusions

This systematic review allowed to conclude that residues from MAPs processing can be used in:

1. Energy production through direct burning, making of briquettes after drying, pelletizing and gasification or in biomethanization and pyrolysis processes to obtain biodiesel and biochar, also for energy purposes.
2. Crop Management. Solid residues can be submitted to composting, vermicomposting, anaerobic co-digestion, and anaerobic digestion. They can also be used to produce biochar adsorbent by pyrolysis, as biosorbents, as soil organic cover or to weed management. Hydrolates can be valorised as eco-friendly biopesticides.
3. Chemical Industry, namely in the production of anthraquinones, platform molecules, and enzyme synthesis.
4. Food industry, both animal and human consumption. Their use in animal feed influenced *T. molitor* and aquaculture species' growth performance. Some by-products can be incorporated as supplement additive for the preservation of food.
5. Pharmaceutical and Cosmetic Industry, since they are valuable sources of phenolic compounds of interest, such as terpenes, phenolic monoterpenes, phenolic diterpenes, flavonoids, among others.
6. Further applications such as production of paper, wood-based panel industry, composites synthesis, wastewater treatment, and in building materials.

Thus, regarding practical implications, this research provides a comprehensive description of possible solutions to valorise MAPs residues for more sustainable waste management practices that also offer new business opportunities.

Despite the wide range of possible applications, further investigation is needed to assess the effectiveness of circular economy approaches with MAPs residues in real cases of industrial applications and the economic viability.

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