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Sustainable Agricultural Practices for the Production of Medicinal and Aromatic Plants: Evidence and Recommendations

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Abstract: As the demand for medicinal and aromatic plants (MAPs) increases, so does the pressure to intensify production, increasing the risk of overexploitation of these natural resources. Therefore, both consumers and companies must commit to sustainable practices. Since sustainable practices in MAP production are scattered in the literature, this study aims to provide a comprehensive compilation of agricultural practices to improve sustainable performance in productive activities. This study collects recommended practices for cultivation, harvesting, drying, extraction of essential oils, and packaging, based on guidelines published by the World Health Organization, the European Herb Growers Association, and the European Medicines Agency, and presents complementary information from scientific papers and the Food and Agriculture Organization. Since the circular economy is considered one of the solutions to foster sustainability, the potential for valorising residues from MAP processing is also highlighted. This study allowed us to identify a set of key parameters that should be monitored in MAP production, which may be a starting point for designing a sustainability assessment tool for the sector. By presenting examples of circular economy approaches, this research can help producers to identify new business opportunities.

Keywords: medicinal and aromatic plants; sustainability; circular economy; residue; practices

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1. Introduction

The literature has been pointing out the significant value of medicinal and aromatic plants (MAPs) all over the world [1]. According to data from the International Trade Center, world trade in MAP resources is predicted to grow annually at a rate of 10 to 12% [2]. The herbal medicine market is one of the fastest growing in the world, with demand increasing inclusively in developing countries. This notable growth has to do with the preference for natural products for health benefits since they are considered safer and more cost-effective than synthetic pharmaceutical drugs [3].

Moreover, as stated by the World Health Organization (WHO), between 75 and 80% of the world's population relies on herbal medicines to meet their primary healthcare needs. Moreover, because of world population growth, it is expected that the global market of medicinal plants will continue to rise [3].

MAPs play a relevant role in healthcare purposes and in economic development, and they are a key generator of rural employment [1].

On the other hand, with the growth in demand comes the pressure to intensify production, increasing the risk of overexploitation of these natural resources.

Overexploitation, in turn, can generate changes in patterns in the structures and population dynamics of extracted species, which affects their growth and reproductive capacity and may even lead to the loss of existing populations, also resulting in the loss of multiple ecosystem services [4].

Given that agricultural activities exert influence on the natural environment such as loss of biodiversity, climate change, and water pollution, companies in this sector must develop sustainable strategies that allow for increasing resource efficiency in production [5,6].

The term "sustainability" etymologically derives from the Latin verb "*sustinere*", which means to maintain and ensure that a certain thing lasts, as well as to assume a commitment in this sense. Thus, sustainability corresponds to the preservation of something that exists in the present and that must be maintained in the future, involving accountability and commitment [7]. However, to preserve the conditions and essential goods for the survival of future generations, it is necessary a commit to the adoption of sustainable practices by consumers and companies.

In the agricultural sector, the implementation of sustainable practices is essential to ensure global food security [6], combat climate change, and reduce or eliminate risks associated with intensive agriculture, namely the overexploitation of natural resources, degradation of air quality, and the emergence and development of various diseases [8].

Particularly, in the MAP sector, the adoption of more sustainable practices can reduce the consumption of energy and time in productive activities while reducing the negative environmental impacts, such as the large-scale proliferation of microorganisms, production of greenhouse gases, and loss of energy potential, among other harmful effects on the environment and human health [9].

Sustainable practices can also result in economic gains through circular economy strategies that encourage the reuse of materials whenever possible to formulate new products or to reintroduce them in productive activities [10].

Once agro-industrial waste in the MAP sector has a considerable potential for being valorised, circular economy approaches can be a fundamental strategy for the development of sustainable industrial processes, while simultaneously generating economic benefits [9,11].

Given that sustainable practices in MAP production are scattered in the literature, this paper aims to provide a compilation of agricultural practices that promote sustainability in MAP production, namely in cultivation, harvesting, drying, extraction, and packaging activities, and to highlight the potential for valuing MAP processing residues. The mentioned guidelines contained in this study may work as footstones for making a workable plan regarding sustainable MAP agriculture and processing. Currently, investigation of sustainable agriculture should be focused on how to apply what is already known theoretically [12]. Bearing that in mind, this research work makes a novel and significant contribution to the field of sustainable agriculture in MAP production. Combining existing scientific and empirical knowledge and presenting circular economy principles, it highlights the importance of responsible practices for preserving the environment, safeguarding human health, and ensuring the continued availability of MAPs.

In the second chapter, good practices are presented based on proposals published by the World Health Organization (WHO) [13] (for medicinal plants), the European Herb Growers Association [14,15] (for MAPs), and the European Medicines Agency [16] (for medicinal plants/herbal substances). Complementary information was included based on scientific papers and Food and Agriculture Organization (FAO) guidelines.

In the third chapter, waste recovery strategies obtained from different stages of MAP processing are presented. Under a circular economy approach, the presented strategies can promote economic advantages by converting waste into value-added products, reducing costs in the waste treatment process and preventing environmental pollution [11]. In the fourth chapter, the implications and limitations of the results are discussed, and recommendations for further research are presented. The last chapter gives some final considerations.

2. Productive Activities

This section states practices that promote sustainability in productive activities in the MAP sector, namely in cultivation, harvesting, drying, extraction, and packaging.

2.1. Cultivation

Cultivation, i.e., MAP production in the field, must involve standardized practices to ensure high-quality production [14].

The necessary growing conditions and duration will vary, depending on the quality of the plant materials. In the absence of published or documented scientific cultivation data, traditional cultivation methods should be followed whenever possible. Otherwise, producers should investigate which conditions and duration of cultivation are ideal [13].

Where appropriate, conservation agriculture techniques should be followed [13], which contribute to environmental conservation as well as improve agricultural production. Guidelines provided by the FAO [17] are presented in the next subchapter. Although these guidelines apply to agriculture in general, they are presented to clarify practical techniques for conservation agriculture, as recommended by the WHO for medicinal plant production [13].

2.1.1. Conservation Agriculture

Due to intensive agricultural production in many countries, soils have become depleted to the point of compromising future production in these areas. Maintaining soil health is critical to the development of sustainable and resilient agricultural production systems.

Conservation agriculture is 20 to 50% less labour-intensive and implies lower energy consumption and greater nutrient use efficiency. This type of agriculture contributes to reducing greenhouse gas emissions and, at the same time, stabilizes and protects the soil from degrading and releasing carbon into the atmosphere [17].

Figure 1 presents the three interrelated principles of (1) conservation agriculture: minimization of soil mechanical disturbance; (2) effectiveness of permanent organic cover of the soil; and (3) diversification of species.

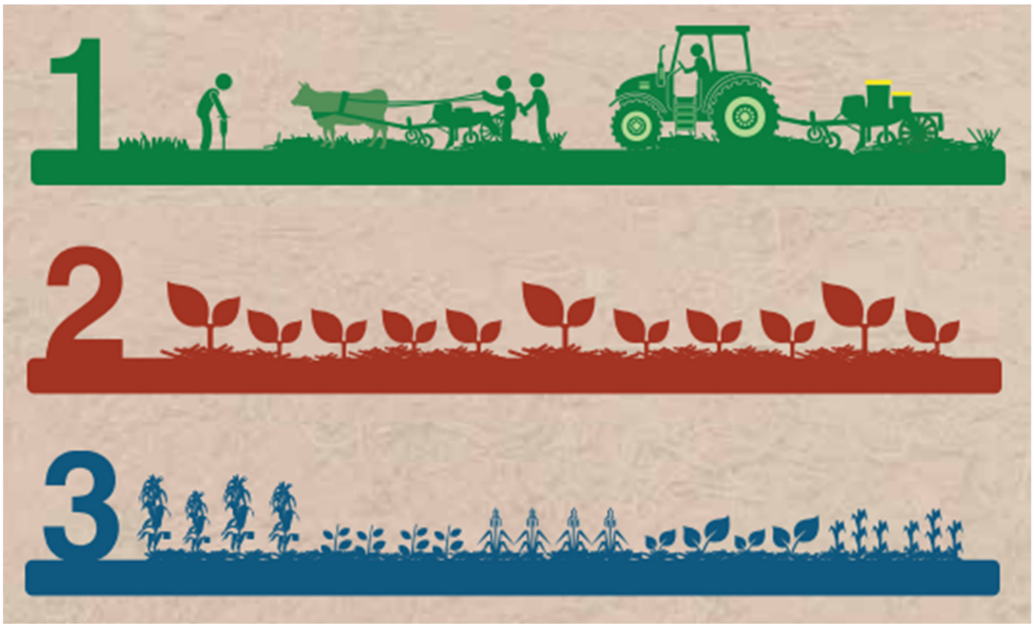

Figure 1. Principles of conservation agriculture [17].

According to the first principle, mechanical soil disturbance (i.e., zero tillage) should be minimized by sowing and/or directly applying fertilizers. Following a "no-tillage" system where appropriate [13] reduces erosion and preserves soil organic matter [17].

The second principle is to make a permanent organic soil cover (at least 30%) with crop residues and/or cover crops. In conservation agriculture, green manure/cover crop residues are always left on the soil surface and are incorporated biologically, without using agricultural tools [18].

Vegetation cover, dead or alive, creates a microclimate that slows the decomposition of organic matter, favouring its accumulation in the soil, in addition to reducing the loss of organic matter through erosion [18].

Thus, maintaining a protective layer of vegetation on the soil surface eliminates weeds, protects the soil from the impact of extreme weather patterns, helps preserve soil moisture, and prevents soil compaction [17].

The third principle of conservation agriculture is species diversification through multiple crop sequences and associations involving at least three different crop species. A well-planned crop rotation promotes good soil structure, promotes a diverse range of soil flora and fauna, contributes to better nutrient utilization, and helps prevent pests and diseases [17].

In the following sections, important additional procedures in MAP cultivation are mentioned.

2.1.2. Site Selection

Due to the influence of soil, climate, and other factors, plant materials derived from the same MAP species can exhibit significant differences in quality when grown in different locations. Thus, external environmental conditions, including ecological and geographic variables, must be considered when choosing a planting site [13].

Risks of contamination resulting from soil, air, or water pollution by harmful chemicals must be avoided. The impact of previous land uses on the growing site, including the planting of previous crops and any applications of plant protection products, should be assessed [13].

2.1.3. Ecological and Social Impact

The quality and growth of MAPs can be affected by the presence of other plants, other organisms, and human activities. On the other hand, MAP agriculture can affect the ecological balance, especially the genetic diversity of plants and animals in the surrounding area. For example, the introduction of cultivation of non-native medicinal plant species could have a negative impact on the biological and ecological balance in the area. Therefore, the ecological impact of agricultural activities over time should be monitored whenever possible [13].

In addition, the social impact of agriculture on local communities should be considered to ensure that negative impacts on local livelihoods are avoided. In terms of profit opportunities locally, small farming is often better than large production, especially if small farmers are organized to market their produce together. If the cultivation of medicinal plants is to take place on a large scale, care must be taken to ensure that local communities benefit directly from, for example, fair wages, equal employment opportunities, and capital reinvestment [13].

2.1.4. Climate

Climatic conditions greatly affect the physical, chemical, and biological traits of plants. Thus, the duration of sunlight, average precipitation, and average temperature, including diurnal and nocturnal temperature differences, must be known in advance [13].

2.1.5. Soil and Fertilization

The soil must contain adequate amounts of nutrients, organic matter, and other elements to ensure optimal growth and quality of the plants. Optimal soil conditions, including soil type, drainage, moisture retention, fertility, and pH, vary according to the MAP species selected and/or the target plant part [13]. However, the precautions mentioned below contribute to maintaining the quality of soil and vegetation in general:

- MAPs should not be grown in soil contaminated with silt, heavy metals, tailings, plant protection products, or other harmful chemicals. Any chemicals used to stimulate growth or protect the crop should be minimized [15,16].

- Manure must be fully composted to meet safe health standards, with acceptable microbial limits, and must be free of human faeces due to the potential presence of infectious microorganisms or parasites [13,16]. Any use of animal manure must be documented [13].
- All other fertilizing agents should be used sparingly, according to the needs of each species and to minimize soil leaching [16]. Chemical fertilizers should only be used if approved by the countries of cultivation and consumption [13].
- It is necessary to ensure the use of appropriate types and amounts of fertilizers (both organic and chemical) through agricultural research [13]. Obtaining documented information about the type and amount of fertilizer used and the results obtained can help determine the appropriate amount to use.
- To promote soil conservation and reduce erosion, producers should create streamside buffer zones and plant cover crops and "green manure", such as alfalfa [13].

2.1.6. Irrigation and Drainage

It must be considered that:

- Irrigation should be controlled and carried out according to the needs of the plants [16], namely herbs' periods of growth and development, climatic conditions, and soil dampness [13].
- Water used for irrigation should comply with regional/national quality standards [16].
- The farmer should pay attention to the quality of irrigation water. Irrigation water must comply with established quality standards and be as free as possible from pollutants [15].

2.1.7. Field Maintenance and Plant Protection

To promote correct field maintenance and protect plants, the following should be considered:

- The crop must be adapted to the growth and needs of the plants [16].
- Insecticides and herbicides should be avoided as much as possible. If application of approved plant protection products is required, the following should be considered:
- Products should be applied at the minimum effective level according to the manufacturer's and authority's recommendations [16].
- The order should only be performed by qualified personnel, using approved equipment [16].
- Information about the order and the pesticide should be documented and made available to the purchaser if requested [15].
- The organization/company carrying out the cultivation must assign someone to check compliance with the processing and sign the necessary documents to accept responsibility [15].
- The minimum interval between this treatment and the time of harvest must be specified by the purchaser or as recommended by the manufacturer of the plant protection product [13].
- Regional and/or national regulations on remaining maximum limits must be respected. If the product is intended for the European market, compliance must be ensured, for example, with *European Pharmacopoeia* regulations, the EU pesticide database, and other European directives (e.g., *Codex Alimentarius*, etc.) [15,16].
- Particular attention should be paid to monitoring and removal of toxic herbs (e.g., herbs containing pyrrolizidine and tropane alkaloid) [15].

2.1.8. Seeds and Propagation Material

To ensure the healthy growth of plants, the following must be considered:

- Seeds and vegetative propagating material must be identified botanically and, to be traceable, the species and, whenever necessary and possible, the subspecies of the plant

variety, chemotype, and origin, must be documented. Recording these characteristics allows for the control and identification of incompatible plants, especially incompatible toxic ones, which should be eliminated as much as possible [15].
- Seeds should have an appropriate degree of purity, vigour, and germination rate so that they are, as much as possible, free from pests, diseases, and (poisonous) weed seeds [15].

2.2. Harvest

A sustainable MAP harvesting system is one in which fruits, seeds, or other plant parts can be harvested indefinitely from a given area without detrimental effects on the structure and dynamics of harvested plant populations [19].

For the sustainable management of MAP crops, the following recommendations must be considered:

- To limit the MAP harvest to a sustainable level, an effective management system must be established that considers annual harvest quotas, seasonal or geographic restrictions, and harvest restrictions to certain plant parts or size classes [20].
- Three factors must be considered when harvesting: the amount to be harvested, the time of harvest, and the condition of the plant community. These three parameters must be selected so that the amount of harvest does not affect environmental processes or the well-being of local communities [13,21].
- Harvest time depends on the part of the plant that will be used. Detailed information on the appropriate timing of sample collection should be consulted, which is often available in the national pharmacopoeia, published standards, formal studies, and major reference books [13].
- The best harvest time should be determined according to the quality and quantity of the bioactive components and not according to the total vegetative yield of the target parts of the medicinal plant [13].

Harvest date has a significant impact on volatile compound content and can be optimized to obtain a higher concentration of essential oils. Harvest dates corresponding to the maximum value of the total concentration of volatile compounds for four types of MAPs, according to the study of El-Zaeddi et al. [22], are displayed in Table 1.

Table 1. Optimum harvest date according to the total concentration of volatile compounds.

Species	Number of Weeks after Planting Date
Parsley (*Petroselinum crispum*)	9
Dill (*Anethum graveolens*)	14
Coriander (*Coriandrum sativum*)	3
Peppermint (*Menthaxpiperita*)	6

- Continuous monitoring and evaluation of harvesting practices should be undertaken to adapt the management strategy as necessary [23].
- Continuous improvement of harvesting techniques should be sought to reduce waste at this stage, avoid loss of quality, and reduce yield [24].
- Harvesting should take place when the plants are of the best possible quality, according to the different uses [14].
- Plants should be harvested in the best possible conditions, avoiding wet soil, dew, rain, or exceptionally high air humidity. If harvesting takes place in humid conditions, the potential adverse effects on the plant should be neutralized [14].
- The harvested plant should not come into direct contact with the ground. If underground parts (such as roots) are used, any adhering soil should be removed from the plant material as soon as it is harvested [13,14].
- During harvesting, care must be taken to ensure that toxic herbs do not mix with the harvested crop [14].

- Materials from decaying medicinal plants must be identified and disposed of during harvesting, post-harvest inspections, and treatment processes to avoid microbial contamination and loss of product quality [13].
- When necessary, large drop cloths, preferably made of clean cotton cloth, can be used as an interface between the harvested plants and the soil [13].
- Equipment used for harvesting must be kept clean and in perfect working order. Parts of equipment/machinery that have direct contact with the harvested crop should be cleaned regularly and kept free of oils and other contaminations, including plant residues [14].
- Cutting devices should be adjusted so that aggregation of soil particles can be minimized [14].
- All containers used for collection must be kept clean and free from contamination from previously harvested medicinal plants and other foreign matter. When not in use, containers should be kept in a dry place and should be protected from insects, rodents, birds, pests, livestock, and pets [13].
- Harvested plants should be collected and transported immediately in dry, clean conditions and in a way that prevents overheating [14].
- Mechanical damage and compaction of the harvested plant, which may result in undesirable changes in quality, should be avoided. In this sense, attention should be paid to cyst overfilling or overcrowding [16].
- The collection organization must assign a person to verify the compliance of the processing with the rules established in the management system [14].

2.3. Drying

Drying consists in reducing water activity to a level that prevents the growth and development of microorganisms that would cause plant deterioration and prevents unwanted chemical reactions from occurring [25]. This processing stage aims to extend the shelf life and preserve the properties of the plants in their fresh state [25]. It also leads to a lower density of plant material and thus lower transportation costs [26]. Furthermore, drying is one of the most important processes in post-harvest processing of MAPs, due to its significant impact on product quality and energy consumption [27].

For drying, natural (in the shade) or mechanical methods can be used, depending on the heat source used. Among the most common processes are natural drying, hot air drying, freeze drying, and spray drying [27,28].

The energy consumption, quantity, and quality of the active ingredients contained in MAPs are affected by the drying method, speed, drying air temperature, and exposure time [27,29]. Thus, the choices of these parameters are an essential economic and environmental criterion.

A few recommendations are listed below:

- Solar dryers are recommended for drying medicinal herbs when it is necessary to reduce or remove moisture from herbs and other medicinal plant parts without affecting their quality for medicinal use [26].
- Freshly harvested material should be transported in clean, dry, and well-ventilated containers as soon as possible to the drying site [14].
- In the case of natural drying in the open air, the crop should be spread in a thin layer. To ensure adequate air circulation, drying racks should be placed at a sufficient distance from the floor. An attempt must be made to obtain uniform drying of the crop and thus avoid mould formation. When drying with oil, the released gases must not be reused for drying. Direct drying should not be allowed, except with butane, propane, or natural gas [16].
- In the drying room, the fresh material should be spread in thin layers on a clean surface (for example, drying racks or plastic cloths), avoiding direct contact with the ground, to protect the material from rain and moisture, other materials (such as other plants

in the surrounding area, stones, dust, plastics, etc.), pollutants (detergents, smoke, allergens, etc.), pests, and pets [14].

- Harvested material that has been spoiled or damaged (which can be identified by bite marks and/or unusual colour, texture, and/or smell) should be excluded [14].
- If possible, the heat source for direct (fire) drying should be limited to butane, propane, or natural gas, and temperatures should be kept below 60 °C. If other sources of fire are used, contact between these materials, smoke, and medicinal plant materials should be avoided [13,16].
- When MAP materials are prepared for use in a dry form, the moisture content of the material should be kept as low as possible to minimize damage from mould and other microbial infections [13].
- When possible, temperature and humidity should be controlled to avoid spoilage of active chemical ingredients [13].
- For indoor drying, the drying time, drying temperature, humidity, and other conditions should be determined, taking into account the relevant plant part (root, leaf, stem, bark, flower, etc.) and any natural volatile components such as essential oils [13,16].
- It must be considered that drying by traditional methods, such as an open-air dryer, reduces the quality of the product while increasing the cost and time of the drying process [30].
- The drying process is characterized by an ideal relative humidity level of 50 to 60% [30].
- Information on the appropriate moisture content of some herbal substances may be available in pharmacopoeia or other formal monographs and should be consulted [13].

To calculate the residual moisture content after drying and compare it with recommended values, producers can use the Gravimetric Determination of Loss on Drying method. Following this method, a sample of material is weighed, dried under defined conditions for an appropriate period, refrigerated, and then weighed again. The residual moisture content (MCr) can be calculated using the following equation [14]:

$$\text{MCr}\ (\%) = \frac{\text{W} - \text{D}}{\text{W}} \quad (1)$$

where W is the mass of the original sample, and D is the mass of the dry sample.

Table 2 presents the residual moisture content (MCr) for different types of medicinal plants as prescribed by the *European Pharmacopoeia* [29,31].

Table 2. Maximum final moisture content (MCr) for some medicinal plants, as described in the *European Pharmacopoeia* [29,31].

Species	Ingredients	MCr (%)
Althaea officinalis L.	Roots	10
Arnica montana L.	Flowers	10
Calendula officinalis L.	Flowers	12
Chamomilla recutita [L.] Rauschert	Flowers	12
Coriandrum sativum L.	Seed	10
Foeniculum vulgare Mill.	Seed	8
Hypericum perforatum L.	Herb	10
Levisticum officinale Koch	Leaves	12
Malva silvestris L.	Leaves	12
Melissa officinalis L.	Leaves	10
Menthaxpiperita L.	Leaves	11
Plantago lanceolata L.	Herb	10
Valeriana officinalis L.	Roots	12
Verbascum phlomoides L.	Herb	12

Achieving the desired final moisture content prevents over-drying and reduces drying time, energy costs, mass loss, and risk of quality deterioration [30].

The correct choice of drying temperature is also an essential economic and environmental criterion to be determined in the drying of medicinal plants, as it influences the herb's properties and energy consumption [29].

Although the required temperature varies for different MAP species, dry air temperatures between 50 and 60 °C appear feasible for drying many medicinal plants [29,30].

Table 3 presents recommended values of drying temperature, moisture content, and air velocity for some MAP species.

Table 3. Characteristics recommended for drying some medicinal plants [29,30].

Species	Drying Temperature (°C)	MCr (%)	Air Speed (m/s)
Purple coneflower	50	0	
Bay leaf	60	10	15
Andrographis		7	
Mint- common	50	0	
Ginger	47.2	10	
Pistachio	21.32		0.8
Coconut copra		7.8	
Hibiscus	32.24	9.2	
Gourd		9	
Garlic	55–75	6.5	0.2
Pepper	55, 60 and 70	10	1.5
Zedoary		6.86	
Spinach	230		
Pear	50–60		
Bitter orange	50–60		
Tarragon	60	10	
Longan	31–58		
Saffron	45 ± 5		
Citronella	60		
Lemongrass	40		
Summer savory	45		

The study by Cuervo-Andrade and Hensel [25] presents a phased drying method, that is, using two temperature values. For drying *Melissa officinalis*, a value of 40 °C was chosen initially, and when the moisture content became 20%, the chosen temperature value became 50 °C until the final moisture content (10%) was reached. This staged drying method provided a 10% reduction in energy consumption and 28.5% in drying time compared to the common method (using a constant temperature value of 40 °C). In terms of quality, this blend contained almost no colour change and showed the same essential oil content as standard drying.

Thus, phased drying methods can be tested to assess whether they are a valid option for reducing energy consumption and drying time.

2.4. Extraction

In processes for extracting therapeutically desirable active ingredients from plants, the appropriate choice of solvent to be used for the extraction, as well as the application of a compatible method, is of great importance [32].

2.4.1. Solvents

Conventional organic solvents such as hexane, ethyl acetate, chloroform, acetone, or methanol, among others, are widely used due to their solubility and extraction power. However, these solvents, in addition to being environmentally hazardous, have direct acute and chronic toxicity, in addition to having carcinogenic potential [32].

To improve health and protect the environment against the risks associated with the use of hazardous volatile organic solvents, alternative means of extraction have been developed.

For example, natural deep eutectic solvents have been recognized as environmentally friendly alternatives to conventional solvents, since they are constituted of metabolites that are naturally present in all types of cells and organisms, namely sugars (glucose, sucrose, fructose, etc.), organic acids (lactic, malic acid, citric, etc.), urea, and choline chloride [33].

In addition to their low environmental impact, they have other advantages such as biodegradability, low cost, simple preparation methods, and the fact that the precursors used are renewable, non-toxic, and natural compounds [32,33].

It should be noted that the green extraction of bioactive compounds from plants using natural eutectic solvents opens interesting possibilities for the development of new drugs, functional foods, and food additives since eutectic mixtures consist of food ingredients that can be applied directly without purification steps [32].

Ionic liquids are also green solvents and have residual vapour pressures over a wide temperature range, high thermal stability, and high viscosity. In addition to being used to provide better profit levels and better processes, these solvents can also be recovered, making it possible to obtain final products with only trace amounts of solvent [32].

However, although they are considered environmentally friendly solvents, attention should be paid to the possibility of ionic liquids reaching soil, surface, and groundwater through spills or accidental effluents [32].

In addition, water, one of the most widely used solvents in extraction processes, is a "green solvent" that, in addition to being environmentally friendly, is inexpensive, technologically acceptable, and offers net advantages in terms of environmental impact, selectivity, run-time, and energy [34,35]. In conclusion, for more environmental and quality procedures, it is important to choose non-toxic solvents.

2.4.2. Methods

In addition to the choice of solvent having implications for the environmental level and the quality of the obtained product, the selection of an appropriate extraction methodology is also important.

The importance of choosing the most appropriate extraction methodology is evident from the fact that when different methods are applied to the same plant material using the same solvent, the extraction efficiencies can vary significantly. The chosen method most appropriate to reach an acceptable degree of reproducibility must also be standardized [32].

Extraction methods can be categorized into two main types: traditional and unconventional (or modern). Generally, conventional extraction methods require the use of toxic organic solvents, long stirring times, and high temperatures (i.e., maceration and distillation processes). The long extraction times and energy consumption associated with processes such as Soxhlet, maceration, boiling, and infusion make them environmentally harmful [32].

On the other hand, modern extraction methods, that is, ultrasound and ultrasound-assisted extraction techniques, are procedures that reduce the consumption of toxic organic solvents and the extraction time. In addition, these environmentally correct methods minimize sample degradation and allow the elimination of unwanted and insoluble components, resulting in higher-quality extracts [32].

Other newer methods, such as microwave solventless extraction, subcritical fluid extraction, and supercritical fluid extraction, are inexpensive, require fewer solvents, and save time and energy [36].

A study comparing the energy efficiency, carbon dioxide emissions, and cost of extraction techniques related to eight plants concluded that the methods assisted by wave-assisted methods, ultrasound, and enzyme-assisted extraction are low-cost, both technically and economically, in addition to being considered more environmentally sound, when factoring in energy consumption and CO_2 emissions, especially in comparison to microwave, supercritical, and pressurized fluid extraction [32].

To attempt to measure the environmental impacts associated with extraction methods, parameters associated with energy efficiency can be used, that is, electricity consumption

(E_C) in kWh and relative electrical consumption ($E*_C$) in kWh g^{-1}. These parameters can be calculated using Equations (2) and (3) [37]:

$$E_C = \frac{P \times t}{1000} \tag{2}$$

$$E*_C = \frac{E_C}{m} \tag{3}$$

where P is energy consumption (W), t is time (h), and m is the mass of essential oil obtained (g).

CO_2 emission (ECO_2) and relative CO_2 emission ($E*CO_2$) are important additional parameters to evaluate different extraction techniques, whose calculation is performed according to Equations (4) and (5):

$$ECO_2 = \frac{E_C \times 800}{1000} \tag{4}$$

$$E * CO_2 = \frac{ECO_2}{m} \tag{5}$$

The calculation of these parameters allows for comparing different extraction methods and estimating the one that involves the lowest relative electrical consumption (E^*_C) and the lowest relative CO_2 emission.

In conclusion, the choice of both the solvent and the extraction method has an impact on the quality of the extraction, on energy consumption, and, consequently, on environmental performance.

2.5. Packaging

After processing, the following precautions should be taken:

- Medicinal plant materials should be packaged as quickly as possible to prevent damage to the product and to protect it from potential pest attacks and other sources of contamination [16].
- To eliminate unwanted materials before and during the final stages of packaging, continuous process quality control procedures must be implemented [13]. Moreover, it is recommended to place stored crops preferentially on pallets and guarantee they are away from the roof, walls, and floor [14].
- Batch packing records must be kept for three years or as required by national and/or regional authorities, which include product name, place of origin, batch number, weight, job number, and date [13].

In addition, precautions must be taken regarding packaging materials and labels, as described in the following subchapters.

2.5.1. Packing Materials

- After final inspection and disposal of any foreign matter, the product should be packed in clean and dry bags, sacks, bales, or cans suitable for food, preferably new [15].
- Packaging materials should be stored in a clean, dry, pest-free place, inaccessible to livestock, pets, and other sources of contamination. Moreover, it must be ensured that the product is not contaminated with the packaging material (especially in the case of a fibre bag) due to losing plastic fibres, chemical residues, strange odours, or any kind of household waste [14–16].
- Packaging materials must not be contaminated [13]. If the material is reusable, it must be carefully cleaned (disinfected) and dried before use. It must be ensured that the reuse of bags does not cause contamination [15].
- When packaging, follow standard operating procedures and national and/or regional regulations of the producing countries and the end user [13].

- It is recommended that fragile medicinal plant materials be packed in rigid containers [13].
- Whenever possible, the packaging used should be agreed upon between the supplier and the purchaser [13].

2.5.2. Label

- The label must be visible and permanently attached and must be made of a non-toxic material [15].
- The information on the label must comply with relevant national and international labelling regulations. Labels must display the following information [13,15]:
- The common and scientific name of the plant.
- Used parts of the plant.
- The name and address of the product.
- Production batch number.
- Quantitative information (e.g., package weight).
- Preservation techniques (if any).
- Place of origin, i.e., place of cultivation or assembly.
- Date of cultivation or collection.
- Hazard information (if any).
- Packing and moving arrangements (if any).
- In the case of organic products: the organic certificate control number.
- Information indicating quality approval and compliance with other national and/or regional labelling requirements.
- Additional information on production standards and quality of medicinal plant materials can be added in a separate certificate attached to the package with the same batch number.

2.5.3. Shelf-Life Extension

To extend the shelf life of herbs, it is recommended to follow the instructions available online on the EUROPAM website [15]. For example, experience shows that incorporating kinetin encapsulation pretreatment measures can improve the minimal shelf life of treated coriander leaves [38]. In addition, ozone treatment is recommended, in addition to the use of electron beam radiation, as the effect of the latter on microbial populations and organoleptic properties increases the shelf life of the sample [39,40].

For dried spices and herbs, an analysis by Karam et al. [41] determined the following classification of bacterial contamination: imported samples had the lowest percentage, followed by samples packaged locally in companies with food safety management systems, followed by samples packaged locally in companies without food safety management systems, and unpackaged samples had the highest percentage.

Moreover, after using some aromatic herb samples (freshly harvested products) to evaluate the quality characteristics, stored for 10 days in refrigerated conditions (3 °C ± 1), it was found that during storage the samples maintained their appearance and colour throughout their shelf life [42]. However, a comparative study of herbs, with and without open packaging, at storage temperatures of 3 to 10 °C concluded that packaging with a storage temperature of 10 °C is recommended to extend the shelf life of herbs [43]. Generally, essential oils or compounds made from them are incorporated into edible coatings to extend the shelf life of the food product [44].

3. Waste Valorisation

This chapter presents the applications proposed by scientific articles for the valorisation of residues obtained in the distillation process and other stages of processing. Waste recovery technologies promote the use of environmentally friendly and scalable materials for industrial use, with a relatively low cost of raw materials, which contributes to their economic viability [45]. Several products/outputs including energy, soil amendments, and chemicals can be generated from the treatment and use of MAP residues. The waste management strategies described in this chapter also reveal the great potential for waste from MAP production in applications in food, pharmaceutical, cosmetic, and other industries.

3.1. Distillation

Essential oils can be obtained from the hydrodistillation process, whereby the essential oil is separated from plant biomass [46]. In the process of hydrodistillation, an aqueous phase (hydrolat) arises, which is distilled with the essential oil, and is physically separated from the essential oil [47]. From hydrodistillation, an undistilled aqueous phase (decoction) resulting from the boiling of plant biomass is obtained. Although the aqueous phase is often disposed of with the non-distilled aqueous phase and plant residues [47], residues from the distillation process have been increasingly considered, as they have interesting bioactivities and add additional value under a circular economy approach [48]. In hydrodistillation, the residues shown in Figure 2 are generated.

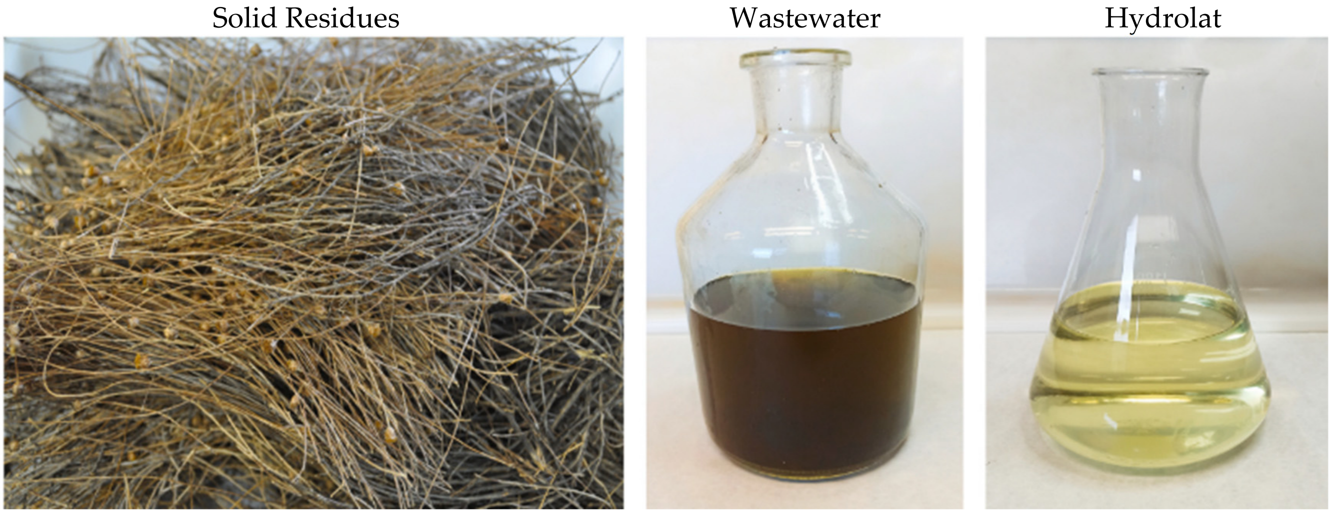

Figure 2. Hydrodistillation residues of medicinal and aromatic plants. Source: [49].

Some strategies for reusing these wastes are presented in this subchapter.

3.1.1. Solid Waste

The solid residue of plant biomass from the hydrodistillation process can be directly used for power generation through direct combustion, making briquettes after drying, pelletizing, and gasification (fuel gas production). Indirectly, these residues can be used for energy purposes in the bio-methanation and pyrolysis processes to obtain biodiesel and biochar [46,50].

The treated biomass, free from oil, can be composted, which contributes to restoring and maintaining soil fertility and to controlling soil diseases caused by microorganisms or cellulose production [46,50].

Solid waste can also be used as an absorbent, animal feed, or food supplement, as a mulch for microorganisms, or to control weed growth to produce bio-aggregates for building materials and in biotechnology applications, i.e., enzyme production [49–51].

Since the solid waste is free of volatile compounds, it can be considered a low-cost, odourless material. Because odorous ingredients can impair the sensory properties of a product or lead to rejection problems when provided in animal feed, solid waste has beneficial potential in the food industry [49].

Other potential industrial applications for the solid residue from MAP distillation are listed below:

- The solid residue from the water distillation of rosemary (*Rosmarinus officinalis* L.) can be used as an antioxidant supplement for pregnant ewes to reduce fat oxidation in

meat. Furthermore, the European Commission considers this residue as a semi-natural food preservative additive (regulated under code E-392) [49].
- Solid residues from the distillation of lavender (*Lavandula angustifolia*) and lavandin (sterile mixture of *L. angustifolia* × *L. latifolia*), i.e., straw, are cheap, readily available, and useful industrial by-products for the production of high-value compounds as platform particles (such as antioxidants) and fungal enzymes involved in the decomposition of lignocellulosic biomass, which have potential as raw materials for the green chemistry industry [52].

3.1.2. Liquid Waste

Hydrolats are a good source of active compounds which in turn can be profitably used to make environmentally friendly bio-insecticides because they contain ketone alcohols, phenol ethers, and methyl ether groups that can be recovered to increase yield [49].

For example, one study found that *Origanum majorana*, *Mentha pulegium*, and *Melissa officinalis* hydrolats showed a repellent effect, despite having very low toxicity against the peach aphid (*Myzus persicae*) [51].

Other uses of these residues associated with specific types of MAPs are listed below:

- Hydrolats from different parts of the elderberry (*Sambucus nigra*) can be used in therapeutic applications due to their pH and trace amounts of the oils. The hydrolats obtained are milder therapeutic agents than essential oils, non-toxic, and therefore ideal for use as a skin tonic or for therapeutic baths [53].
- The hydrolat from the hydrodistillation of lemongrass (*Sympopogon citrate*) is composed of an essential oil rich in emulsified citral, making it a suitable ingredient for food applications. This hydrolat can be used as a functional ingredient in formulations of matcha tea in compliance with beverage safety regulations [47].

In addition, through the aqueous distillation of lemongrass (*Cymbopogon citrate*), it is possible to obtain a non-distilled aqueous phase resulting from the boiling of plant biomass (decoction), with antioxidant and anti-inflammatory properties, phenolic compounds, and polysaccharides rich in glucose. These properties make it possible to apply this by-product as a functional dietary fibre in the food industry [47].

- The liquid distillation residue of basil (*Ocimum basilicum* L.) contains phenolic compounds, such as rosmarinic acid and caffeic acid, and can be used in the cosmetic and pharmaceutical industries [51].
- Rosemary (*Rosmarinus officinalis*) hydrolats that are aromatic and have antioxidant properties are used directly on the skin and hair or incorporated into cosmetic formulations [54].

The various applications mentioned so far contribute to waste reduction, climate change mitigation, soil carbon sequestration, soil stabilization, soil quality improvement, provision of a range of ecosystem services, and remediation of areas contaminated by heavy metals [46].

3.1.3. Waste Extraction

Re-extraction of the active ingredients is another method that can increase the economic value of MAPs and reduce the entry of chemicals into the environment during waste disposal. Since many bioactive compounds remain in the waste, even after decoction or extraction, it is important and necessary to perform a new extraction process [9,55].

Different solids extracts showed germination-stimulating, antioxidant, antifungal, antibacterial, and anti-inflammatory properties. Extracts from these by-products have also been suggested as food preservatives [49].

By extracting these biomasses using food solvents (ethanol and water), it is possible to recover the polyphenols. Moreover, antioxidant and anti-tyrosinase activities can be exploited in the food and cosmetic industries to prevent the browning and degradation of active compounds and to improve the preservation of the final products [49].

Due to their anti-enzyme properties, some biomass extracts are suitable for various applications in the food, cosmetic, and pharmaceutical industries [56].

For instance, the distilled solid residues of rosemary (*Rosmarinus officinalis* L.), sage (*Salvia fruticosa* L.), and peppermint (*Mentha spicata* L.) are rich in bioactive compounds with antioxidant activity, mainly polyphenols, which can be valued through extraction methods and green distillation for applications in the food, cosmetic, and pharmaceutical sectors [57].

The hydroethanolic extract from the residues generated in the distillation of the aerial parts of oregano (*Origanum vulgare* var. *aureum* L.) and thyme (*Thymus vulgaris*, var. Doone Valley) plants has a high phenolic content, being a valuable source of biologically active compounds. The phenolic compounds present in the extract can be used as antioxidants in food and pharmaceutical products [58].

Some hydrolat extracts have biological properties such as nematicide, insecticide, antibacterial or antifungal, antioxidant, and anti-inflammatory, which favours their application as a medicinal treatment for hyperlipidemia and cardiovascular diseases [49].

Wastewater extracts (i.e., the water that has been in contact with the aromatic plant during distillation) can exhibit antioxidant, antifungal, antibacterial, enzymatic, and anti-inflammatory biological activities. For this reason, the application of these extracts is also proposed in food additives, cosmetics, or even medicinal treatments [49].

Namely, the residues of *Sophora flavescens* (a plant used in traditional Chinese medicine), after extraction under heating and decoction with distilled water, contain flavonoids that can be re-extracted by ultrasonic waves with ethyl acetate. In addition, the anti-inflammatory activity of these residues makes their reuse in the food additives, medicines, and cosmetics industries relevant [55].

By extracting post-distillation residues from thyme (*Thymbra capitata* L.) with methanol, including plant residues and liquids, it is concluded that these residues are an effective potential source of polyphenols, as natural antioxidants have properties beneficial to human health and can be useful in substituting or even reducing synthetic antioxidants in foods, cosmetics, and pharmaceuticals [59].

In the next subchapter, potential uses for other types of waste obtained from MAP processing are presented.

3.2. Other Waste

In addition to residues from distillation, residues generated in the harvesting, drying, and processing stages can be valorised.

One study found that in corn crops, compost from Chinese herbal medicine residue can be used as an effective organic fertilizer and replace up to 50% of the amount of chemical fertilizer usually applied. The application of these residues in crops is an effective recycling strategy and allows for the management of nutrients that improve soil fertility and reduce the use of chemical fertilizers. The use of these residues has contributed to protecting the environment, reducing soil nutrient loss, and enhancing crop yields [60].

In addition, the use of industrial MAP by-products in agricultural practices is a possible way to prevent the growth of major plant pathogens in soil [61].

The conversion of organic waste from the harvesting, production, and processing of medicinal plants can constitute a high-quality organic fertilizer. One study showed that the application of compost, produced from the organic waste of the processing of medicinal plants, to pot marigolds (*Calendula officinalis* L.) improved the yield and quality characteristics of the plants as if they were fertilized with commercial fertilizers [62].

Another study showed that it is possible to valorise all residues of rosemary (*Rosmarinus officinalis* L.), common sage (*Salvia officinalis* L.), and basil (*Ocimum basilicum* L.) obtained in cultivation and processing. These residues include whole basil plants at the end of the cycle, rosemary pruning residues, and all prepackaged green residues (leaves, stems, and inflorescences) from basil, rosemary, and sage [50].

The fresh biomass of the aromatic residue was cut into small pieces and then subjected to hydrodistillation. Essential oils recovered from waste retained all the positive properties of the specific aromatic plants used in the study, although they were not collected at the balsamic stage [50].

The solid residues from the steam distillation of the three species were used to obtain composting. The study also concluded that the aromatic water recovered at the end of steam distillation of these plants is an easy-to-use product, as it has a species-specific aroma [50].

Therefore, as demonstrated in this study, it is possible to valorise all cropping and processing residues by combining different strategies, according to the principles of a circular economy.

Additional options for recovering residues, from processing different types of MAPs are listed below.

- Although the roots of lovage (*Levisticum officinale* W.D.J. Koch) are generally discarded, they can be a source of valuable bioactive compounds, such as phthalides and phenolic acids, and offer biological properties worth exploring, which can lead to a circular economy in the food and/or pharmaceutical industry [63].
- The alcoholic extract of elderflower (*Sambucus nigra*) has good antioxidant activity, and the glycerine extract contains appreciable amounts of anthocyanins and other nutrients. The evaluation of the antimicrobial activity of the extract reveals the great potential of bioactive compounds as nutraceuticals, drugs, and cosmetics for therapeutic purposes [53].
- Tobacco (*Nicotiana tabacum*) processing waste can be transformed into new raw materials. Compounds are found in tobacco that exhibit important biological activities, including resistance to many diseases, human health regulation, sterilization, and pest control. The wide range of application scenarios gives by-products of the tobacco processing industry a high potential for recovery [64].
- The use of residual hemp (*Cannabis sativa* L.) biomass as an alternative and renewable lignocellulosic raw material in the manufacture of lightweight board products is a fundamental principle of the circular economy and an environmentally sound strategy to deal with the increasing scarcity of resources in the wood-based board industry [65]. In addition, hemp residue can be used for composting, incineration, and anaerobic digestion [66].
- Pine bark and buds, previously considered inappropriate waste, have been identified as a rich source of natural polyphenols, which have beneficial nutritional, medicinal, and health properties [67].

Pine (*Pinus pinaster*) bark extracts exhibit pharmacological properties, i.e., photoprotective and anti-photoaging activities. In food applications, studies have revealed that pine bark extract significantly improved the oxidative stability of cooked meat and inhibited bacterial growth when used as a supplement to fruit juice, acting as a shelf-life extender. Pine buds can also be a valuable raw material for preparing nutritional infusions. Products based on pine buds, such as juices, beer, and tea, are already on the market [67].

- The roots of the aloe vera plant (*Aloe barbadensis* Miller), due to its quinone content, have pharmacological significance and antiviral activity [51].
- A study suggests including the ethanolic extract of the solid remains of female *Santolina chamaecyparissus* as a natural ingredient for the development of natural coatings to preserve cheese and prevent oxidation and fungal development [49].
- The use of ethanolic extracts from solid residues of lavender (*Lavandula angustifolia*) and lemongrass (*Melissa officinalis*) has the potential to extend the shelf life of bread [49].
- After extraction of essential oils from the aerial parts of *Lavandula angustifolia* and *Lavandula x intermedia*, a biomass is obtained which, although frequently used for vegetation

in other crops or energy production through combustion, is still rich in polyphenols and represents an interesting source of bioactive compounds, although they may have been partially lost during the steam distillation process. Due to their anti-enzyme properties, the biomass extracts used to extract the essential oils may represent a valid therapeutic alternative for the prevention and treatment of Alzheimer's disease, hyperpigmentation, and other chronic diseases where the roots play a major role. Thus, since they are important sources of bioactive compounds, these extracts are suitable for various applications in the food, cosmetic, and pharmaceutical industries [56].

4. Discussion

The main practices regarding each productive activity, namely cultivation, harvesting, drying, extraction, and packaging, are summarized in this section.

To boost sustainable performance in MAP processing, it is recommended to:

- Follow standard practices or traditional methods. Apply conservation agriculture principles.
- Consider permanent organic soil cover and species diversification to promote soil health and prevent pests and diseases.
- Consider the external environmental conditions and avoid the risks of pollution.
- Consider the environmental and social impact on local communities and monitor the impact over time.
- Know in advance the duration of sunlight, average precipitation, and average temperature, including temperature differences during the day and night.
- The crop must be adapted to the needs of the plants, and the use of pesticides and herbicides should be avoided. Particular attention should be paid to weeding.
- Seeds and vegetative propagating materials must be identified botanically and have an appropriate degree of purity and vitality.

To promote sustainable harvesting, producers should:

- Assure that the number of harvested MAPs does not affect environmental processes or the welfare of local communities.
- Create an effective management system that considers:
    - Quantity harvested.
    - Harvest season.
    - Condition of the vegetal community.
- Promote continuous improvement of harvesting techniques to reduce waste at this stage, avoiding loss of quality and yield reduction.
- Keep all containers and tools used in harvesting clean and free from contamination.
- Avoid unwanted alterations in plant quality during collection and post-harvest transportation.
- Checking the compatibility of processing with the established effective management system.

Regarding drying, the following practices are recommended:

- Determinate, control, and verify the basic economic and environmental criteria in the drying process that affect energy consumption and the quantity and quality of the active ingredients of the plants, namely:
    - Drying method.
    - Airspeed.
    - Air temperature.
    - Exposure time.
- Ensure optimal final moisture content to avoid over-drying and reduce drying time, energy costs, mass loss, and risk of quality degradation.

Concerning extraction, producers should:

- Choose non-toxic solvents.
- Estimate relative CO_2 emissions associated with extraction methods and prefer methods with greater energy efficiency, lower CO_2 emissions, and lower cost.

In summary, the following sustainable packaging practices stand out:

- Keep packaging materials and storage areas clean and dry.
- Uncontaminated packaging materials are preferred.
- Ensure that reuse does not cause contamination of the product.
- The label must be made of non-toxic material and must contain the relevant information.
- If appropriate, integrate packaging pretreatment measures that extend its shelf life.
- Follow food safety management system standards applicable to packaging.
- Maintain proper storage temperature (10 °C is a recommended value) to prolong the shelf life of herbs.

This research also exhibited the potential to reuse residues from MAP processing. Solid residues have the potential to be used in the following applications:

- Energy purposes through direct combustion, making briquettes after drying, pelletizing, gasification, and in methanol and pyrolysis processes to obtain biodiesel and biochar.
- Composting.
- Cellulose production.
- Biosorbents.
- Bio-aggregates for building materials.
- Fodder or nutritional supplements for animals.
- Food industry as preservatives.
- Chemical industry in the production of enzymes and platform molecules.

The liquid residues can be used as follows:

- Eco-friendly bio-pesticides.
- Liquid fertilizers.
- Functional dietary fibre and functional ingredient in matcha tea formulations in the food industry.
- Sources of phenolic compounds such as rosmarinic acid and caffeic acid in the cosmetic and pharmaceutical industries.

Regarding the recovery of waste extracts, the following aspects stand out:

- Solid residue extracts showed antioxidant, antifungal, antibacterial, anti-inflammatory, and germination-stimulating properties as food preservatives suitable for various applications in the food, cosmetic, and pharmaceutical industries.
- Hydrolat extracts contain biological properties such as nematocidal, insecticidal, antibacterial, antifungal, antioxidant, and anti-inflammatory, favouring their use as a medical treatment for hyperlipidemia and cardiovascular diseases.
- Wastewater extracts contain many antioxidants and antifungal, bacterial, enzymatic, and anti-inflammatory biological activities, which favours their use in food additives, cosmetics, or even medical treatments.

Regarding the recovery of waste from other processing steps, other than distillation, the following aspects are noteworthy:

- Parts of plants that are often considered waste products (roots, bark, and buds) can be a source of valuable bioactive compounds useful in the food, pharmaceutical, and cosmetic industries.
- Residues resulting from harvesting, drying, and processing can be used in composting to obtain organic fertilizers.

It is hoped that the information gathered in this paper will help MAP producers adopt more sustainable production methods, which allow a balanced exploitation of natural resources, preserving ecosystems' well-being while promoting economic development. Moreover, the gathered information may help producers to identify business opportunities based on circular economy approaches.

Concerning theoretical implications, this study can be a starting point for the development of a tool to assess and support the implementation of sustainable practices, since it collects a set of key parameters that should be monitored in MAP production, such as water quantity for irrigation, amounts of fertilizers (both organic and chemical), quantity harvested, harvest season, condition of the vegetal community, drying method, temperature, and the associated exposure time, maximum final moisture content, solvents toxicity, and relative CO_2 emissions associated with extraction methods, among others.

This study allowed us to summarize a set of practices that are recommended for improving the sustainable performance of MAP-sector companies, providing some recommendations for specific MAP species, concerning, for example, optimum harvest date, maximum final moisture content, drying temperature, air speed, and valorisation potential.

Nevertheless, successful implementation of the mentioned agricultural practices relies on a proper evaluation of their efficacy and viability, according to the plant's specific needs as well as the environmental and market conditions.

Further research should focus on methods to support MAP producers' decision making, considering their specific characteristics and needs (through, e.g., data recording and analysis) for an effective implementation of sustainable practices.

5. Conclusions

With the increase in demand for agricultural products and the consequent pressures to increase production, there is a risk of resource overexploitation, which can lead to negative environmental and health effects. To reduce these risks, producers must implement sustainable practices, optimizing the exploitation of these natural resources without compromising their conservation.

This document has compiled a set of agricultural practices applicable to cultivation, harvesting, drying, extraction, and packaging activities, and it has also presented different possibilities for valorising MAP residues. The environmentally correct application of strategies based on waste recovery makes it possible to obtain value-added products and reduce waste treatment costs, enhance economic benefits, and, at the same time, contribute to the well-being of the planet.

It is expected that this research will facilitate the improvement of sustainable performance in the MAP sector, allowing it to attend to the rising demand in this sector with environmental consciousness and efficiency. However, more research is needed to support MAP producers in implementing sustainable practices and to understand the environmental, social, and economic impact of such practices.

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