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Enhancing value through residual biomass from Medicinal and Aromatic Plants

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Abstract

The utilization of medicinal and aromatic plants (MAPs) in agro-industrial processes generates a variety of wastes, including biomass from the distillation of aromatic plants and leftover components of medicinal plants. These biomasses have the potential to be recycled and turned into products with additional value hence they shouldn't be classified as trash. These wastes, especially the underutilized parts of medicinal plants and distillation byproducts, can be enhanced by processing, extraction, hydrolysis, pyrolysis, and fermentation. They are great resources for the extraction of phytochemicals that are useful in medicine, cosmetics, and fragrance, such as phenolic antioxidants. Additionally, the leftover biomass can be used as organic mulch or animal feed. They may also be converted into composts, charcoal, and bio-sorbents, which are effective ways to improve soil and purify wastewater. The use of these leftovers is examined in this article, ranging from industrial applications to technological development at the laboratory scale. Opportunities in the MAPs industry may be unlocked by effectively recycling the leftover biomass from MAPs, which also provides practical waste disposal options and financial advantages.

Keywords: Amoxicillin, degradation, Maximum Tolerance Level (MTL), Antibiotic bioremediation, Bacterial consortium

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Introduction

Every year, the world's agricultural industry produces significant volumes of leftover biomass in the form of solid, liquid, and gaseous materials. This biomass is regarded as one of the world's most plentiful, affordable, and renewable resources. According to Olofsson and Börjesson (2018), residual biomass is the term for biological materials that are accidentally created during a production process and may or may not be regarded as trash. Oil cakes and straw, for example, are considered carbon-neutral since they do not raise atmospheric carbon dioxide levels. They are byproducts of growing minor grain and oil crops. However, reusing leftover biomass is essential to avoid negative environmental effects brought on by inappropriate disposal. Proper management ensures sustainable practices. There are two advantages to using leftover biomass: first, it allows for the extraction of important phytochemicals, and second, it may be transformed into products with additional value. Effective use and recycling of this biomass are crucial in the field of medicinal and aromatic plants (MAPs), as they offer promise for financial gains, environmental sustainability, and societal advantages (Zhu *et al*., 2012). Medicinal and Aromatic Plant (MAP)-dependent industrial and agricultural sectors generate a variety of solid and liquid wastes, such as leftover pieces of medicinal plants and distillation residues from aromatic plants. After preliminary processing, certain portions of medicinal plants are used as raw pharmaceuticals, whereas other plant components are left unused and end up as trash (Fig. 1). The growing need for natural bioactive compounds has spurred research into exploiting leftover biomass from aromatic plants as a new resource, which requires careful planning and execution (Santana-Meridas *et al*., 2012). Aside from the specialist parts like fruits, roots, leaves, and flowers utilized in Ayurvedic and traditional medicines, there is a significant amount of medicinal plant biomass that is lost. By valuing residues, businesses and society are actively working to recover valuable bioactive components from residues while simultaneously reducing residue burdens in the twenty-first century (Galanakis, 2015). The potential of leftover biomass from medicinal and aromatic plants (MAPs) is being aggressively used through both conventional and novel approaches. In this discipline, cutting-edge technologies are constantly being developed. In order to extract valuable chemicals, increase their value, and outline important tactics, this communication attempts to compile and assess a number of novel approaches. It also aims to shed light on current developments and prospective strategies for the all-encompassing use of leftover biomass, emphasizing the continuous attempts to efficiently utilize this priceless resource. A thorough method for managing leftover biomass from medicinal and aromatic plants (MAPs) is described in this paper. In addition to turning, it into a variety of value-added products, including compost, charcoal, biogas, enzymes, and biopesticides, it aims to maximize its usefulness by separating phytochemicals and phenolic antioxidants. Compost and biochar are useful soil amendments, biofuel and biogas help generate electricity, and biopesticides protect crops from insect infestations. These derived products find a variety of uses. By reducing waste and encouraging environmentally friendly behaviors, this comprehensive strategy not only improves resource utilization but also advances sustainability in businesses associated to MAPs (Ercolano *et al*., 2015). This article highlights the industrial use of leftover biomass by separating bioactive components that may be used in cosmetics, medicines, and fragrance. It also explores the crucial function of leftover biomass as a bio-sorbent for the treatment of industrial effluents and wastewater. By efficiently handling the disposal of biomass, these dual applications not only offer financially feasible solutions but also solve environmental sustainability issues. By doing this, it closes the gap between resource use and waste management, providing a viable and sustainable method of managing leftover biomass in a variety of businesses while encouraging environmentally responsible behaviors. Table 1 provides a straightforward calculation of the amount of solid waste generated per unit of essential oil production.

Medicinal and aromatic plants encompass herbal remedies integrated into natural health products across domains like pharmacy, cosmetics, nutrition, medicine, and perfumery. These plants additionally serve as preventive agents, sustaining well-being, and contributing to disease prevention and treatment. Medicinal plants, abundant in nature, are primarily gathered from wild regions to support human health (Uniyal *et al*., 2000). In developing nations, a significant majority (60-80%) relies on traditional or folk medicines derived from medicinal plants to address healthcare requirements. China employs around 5000 plant species, and India utilizes 7000 species within their respective traditional medical systems. Aromatic plants release distinct odours as a result of their essential oil concentration, which is high in terpene chemicals. These fragrant plants are aptly named "aromatic" for their ability to produce distinctive aromas. India boasts approximately 1300 aromatic plant species, yet only around 50 of these, along with their extracted oils, maintain a steady demand within the trade and industrial sectors due to their unique qualities and applications (Basak *et al*., 2018a). Globally, approximately 3000 aromatic plant species have been investigated for essential oil extraction. Nevertheless, in the international market, essential oils from only around 300 aromatic plants are regularly traded due to their widespread usage and commercial viability. Obtaining precise global essential oil production statistics is challenging. Yet, recent estimates suggest a total production of around 104,000 tonnes. Essential oil production data hints at the substantial residual biomass potential generated by the distillation industry (Lubbe and Verpoorte, 2011). Fig 1. depicts a sustainable process where aromatic and medicinal plants are used to extract essential oils and bioactive compounds, while the leftover biomass is converted into phenolic antioxidants, compost, and biochar. This approach promotes zero waste and supports circular bioeconomy practices.

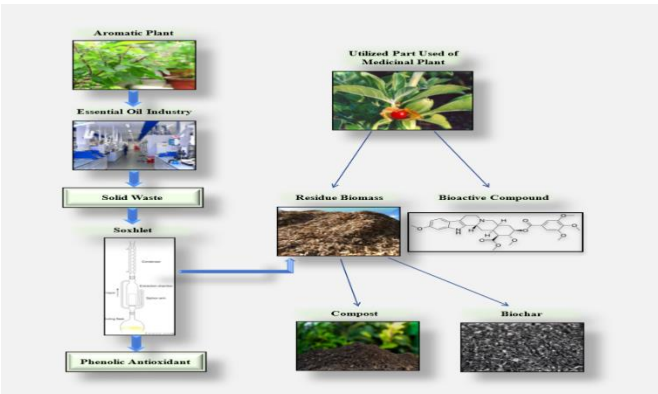

Figure 1. Schematic Representation of Value Addition of Residual Biomass from MAPs.

2. Harnessing Residual Biomass from Medicinal and Aromatic Plants-

2.1 Bioactive phytochemicals derived from the remaining biomass of MAPs - The environment and public health are at risk when leftover biomass from medicinal plants is not properly managed. Nonetheless, the growing need for resources emphasizes how crucial it is to turn these leftovers from medical plants into useful resources. There is little data on phytochemical extraction from non-official plant parts, and most research has concentrated on phytochemical analyses of legitimate plant parts. Therefore, separating pharmaceutical-grade phytoconstituents from leftover plant material offers a significant research opportunity. For example, 10 units of the biomass product, artemisinin acid, are created for every unit of artemisinin. The synthesis of artemisinin has increased fourfold as a consequence of recent advancements at the Max Planck Institute that involves using UV light to regenerate artemisinin from its leftover product, artemisinin acid (Ibekwe, 2009). This technique demonstrates the capacity to effectively extract significant compounds from residual medical plant material. Ashwagandha (Withania somnifera L. Dunal) is recognised for its medicinal properties, especially its roots, which contain alkaloids and withanolides. Recent studies have found that W. somnifera leaves contain withanolides, an anti-cancer medicinal compound (Jayaprakasam *et al*., 2003; Gajbhiye *et al*., 2015). According to Jayaprakasam *et al*., (2003), this plant contains withanamides, which are bioactive substances with antioxidant properties that may offer protection against beta-amyloid-induced cytotoxicity, a condition associated with Alzheimer's disease. Bolleddula *et al*., (2012) discovered novel withanamide and withanolide structures in W. somnifera fruits using mass spectrum data. Reusing wasteful resources like trash, conserving valuable raw materials, and creating new materials are all components of true recycling. Together, these initiatives aim to preserve raw materials while creating novel compounds, supporting both the creation of novel pharmaceutical compounds and the sustainable use of resources.

2.2 Source of Bioactive Phenolic Antioxidants- An important contributor to the availability of antioxidants is the biomass of aromatic plants, which is known to contain phenolic antioxidants. The hunt for new, all-natural antioxidants has been on the rise for the past few decades. One possible solution is to use agro-industrial by-products as antioxidants because they are both inexpensive and safe for the environment (Rached *et al*., 2018; Bistgani *et al*., 2019). The concentration of polyphenols in the distillation biomass is displayed in Table 2. Antioxidants in feed and food, anti-aging ingredients in cosmetics, and other health-enhancing bioactive chemicals are all within the realm of possibility thanks to its high polyphenol concentration. Wasted rose flower and leaf material may have antioxidant, antiradical, and antiacetyl cholinesterase properties, according to studies (Baydar and Baydar, 2013). Research has demonstrated that the lactones herniarin and coumarin, which are extracted from lavender straw, has anti-inflammatory and antispasmodic properties (Tiliacos *et al*., 2008). There is still hope for recovering substantial antioxidants, even if these studies show that by-products have decreased activity compared to the primary plant. Both the fruit and the leaves of the ashwagandha plant, which are not consumed, have antioxidant and phytochemical characteristics (Shrivastava *et al*., 2011, Alam *et al*., 2012).

2.3 Fodder- Ginseng meal, a byproduct of bioactive component extraction from Panax ginseng, is known to contain 16% protein. There is evidence that adding it to the diets of dairy cows and chicks improves milk output and quality (Ju *et al*., 1975). One of the main obstacles in producing animal feed in many underdeveloped countries is the scarcity of protein sources. Researching other resources is essential. Remains of medicinal and aromatic plants (MAP) are rich in beneficial bioactive substances, such as dietary fibers, carotenoids, and polyphenolics. The byproduct of removing essential and bioactive oils is a great source of fiber, cellulose, hemicellulose, lignin, and silica, making it perfect for use as animal feed. Ensiling lemongrass leaves with whey and sugarcane molasses is an efficient way to speed up the production of lactic acid; the leaves are a byproduct of the essential oil extraction process (Ventura-Canseco *et al*., 2012). Psyllium husk is the main product of DE husking for isabgol, an Indian medicinal plant produced from Plantago ovata. Dairy Knowledge Site (2019) reports that the leftover dehusked seeds are a good source of carbs, protein (17-19%), and fatty acids, making them an ideal feed for calves.

2.4 Agrofuels- The rising demand for bio-based fuels, particularly ethanol, is driven by their versatility in both fuel and chemical production. In several nations, ethanol derived from agricultural residues serves as a biofuel, gradually substituting conventional crude oil-based energy sources, reflecting a growing shift towards sustainable and renewable energy solutions (Raj *et al*., 2012). An important precursor for creating furan monomers, such as 2,5-dimethylfuran (DMF), which has exceptional anti-knock qualities and is suited for use as a liquid transportation fuel, hydroxymethyl furfural is produced from aromatic waste by converting cellulose into it (Rout *et al*., 2015). The potential of lemongrass bio-oil as a fuel source was highlighted by Deshmukh *et al*., (2015), who discovered that it had a high heat value and low quantities of PAHs and nitrogen compounds. Fungal techniques that convert distilled straw cellulose and hemicelluloses from lavender and lavandin might also provide a way to make fuel-grade ethanol. According to research conducted by Joyce *et al*., (2015), 198 ml of ethanol was produced per gram of palmarosa (Cymbopogon martini) and 170 ml per gram of lemongrass (Cymbopogon flexuosus) biomass, respectively. Alternative fuels like lemongrass bio-oil have a heating value of 17.2 MJ kg-1. The pre-treatment of aromatic spent biomass with hot steam greatly facilitates the conversion process to ethanol compared to untreated biomass. This benefit emphasizes the aromatic scent's appropriateness as a feedstock for ethanol production, providing a more economical and sustainable approach to biofuel production. (Zheljazkov *et al*., 2018). These findings confirm the dual potential of Medicinal and Aromatic Plant (MAP) waste for both biofuel generation and co-product commercialization, highlighting its versatility in resource utilization.

2.5 Natural pesticides- Environmental and health risks, along with pesticide resistance, have been brought about by the over use of broad-spectrum chemical pesticides. So, there's been a recent uptick in the search for less harmful insect treatments and ways to lessen their impact on business operations. Biologically derived insecticides, or biopesticides, are becoming increasingly common. Recovered bioactive components from Medicinal and Aromatic Plants (MAP) have not been extensively studied for their biopesticide potential, despite extensive research on their antioxidant and pharmacological properties. Studies have shown that hydrosols, a type of solid waste, and other byproducts of the essential oil distillation process have pesticidal properties. One way to measure the effectiveness of pesticides is by looking at their antifeedant impact on important agricultural pests. These pests include the green peach aphid, cotton leafworm, and Colorado potato beetle. Compared to S. littoralis, L. decemlineata is more affected by solid residue from essential oil distillation businesses, according to these results. In terms of antifeedant activity against L. decemlineata, Rosemary officinalis distillation waste extract is superior than S. littoralis and M. persicae (2014) (Santana-Meridas *et al*., 2012). One component of R. officinalis solid residue, carnosic acid, was identified as the principal agent responsible for the activity against L. decemlineata. Hydrosols obtained from aromatic plants containing phenolic compounds showed insecticidal effects. A study conducted by Zekri *et al*. (2016) demonstrated that hydrosols of Mentha suaveolens and Mentha pulegium L. possess potent insecticidal properties against the Toxoptera aurantii (Aphididae) family of citrus pests. Significant effects on mortality and fertility in the key agricultural pests Aphis gossypii and Tetranychus urticae were seen in hydrosols of rue (Ruta chalepensis) and sweet basil (Ocimum basilicum) (Traka *et al*., 2018). Hydrosols of Origanum majorana also killed 10-15% of the Mentha persicae that were tested. Peach aphids, namely Myzus persicae, were shown to be repellant but not harmful to hydrosols of lemon balm, marjoram, and pennyroyal, according to research by Petrakis *et al*., (2015). To completely understand the function of bioactive components and the impact of their combined actions on antifeedant activity, more study is necessary. The use of this resource in integrated pest control strategies can be enhanced by the profile and evaluation of secondary metabolites in hydrosols and distillation residues.

Table 1: Estimated output capacity of primary and secondary leftovers from the essential oil industry

Plants	The volume of Solid residual from essential oil extraction residue	Reference
Santolina	100 kg solid residues /0.25 kg essential oil	Santana-Meridas *et al.*, 2012
Rose Oil	100 kg solid residues /0.033 kg essential oil	Shamspur *et al.*, 2012
Melissa	100 kg solid residues /0.014 kg essential oil	Vasileva *et al.*, 2018
Lavandin	100 kg solid residues /1 kg essential oil	Santana-Meridas *et al.*, 2012
Marjoram	100 kg solid residues/0.5 kg essential oil	Santana-Meridas *et al.*, 2012
Labdanum	100 kg solid residues/0.5 kg essential oil	Santana-Meridas *et al.*, 2012
Chamomile oil	100 kg solid residues/0.3-0.45 kg essential oil	Slavov *et al.*, 2018

2.6 Biochar- Biochar is a pyrogenic substance that is rich in carbon and has great promise as an additive to soil for sustainable agriculture and environmental management in the long run. Greenhouse gases (GHGs) are produced by mulching or burning the residual biomass of medicinal and aromatic plants (MAPs). Reduced environmental risks and higher farmer incomes are possible outcomes of efficient biomass valorization processes. Biochar is gaining prominence as a tool for improving soil fertility, agricultural yields, and pH levels. For example, a cost-effective soil fertility enhancer made from biomass of menthol mint distillation showed a high nutritional content, cation exchange capacity, and calcium carbonate equivalency. Improved crop production, soil quality, and soil characteristics were achieved by combining chemical fertilizer with biochar produced by the distillation of lemongrass. Biochar produced by distilling the biomass of Java citronella also reduced pollution and improved nutrient usage efficiency compared to organic additions. Reducing lead availability and improving soil biological characteristics, especially enzymes vital for remediating polluted soils, are two additional ways biochar helps with soil remediation. In sum, biochar provides a multipronged strategy for ecological preservation and sustainable agriculture. Degraded mining areas have been successfully remedied using biochar produced from lemongrass distillation biomass. According to research by Jain *et al*., its use greatly enhanced soil biological characteristics, especially the stability of enzymes that are essential for cleaning up polluted soils. In terms of nutrient utilization efficiency and plant productivity, biochar from Java citronella distillation biomass outperformed FYM and vermicompost by minimizing nutrient losses (NO3-N, NH4-N, and PO3), according to Yadav *et al*., (2019).

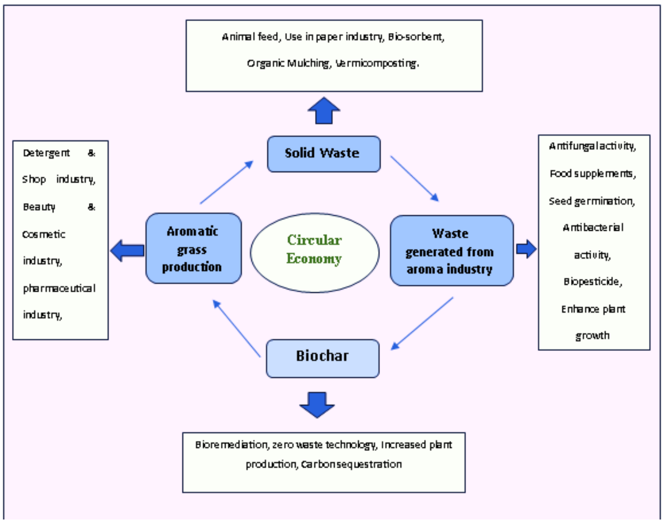

Figure 2- Various Features of Aromatic Plant Production on Degraded Soil Towards a Circular Economy.

2.7 Soil amendments- Soil health can only be improved with natural or organic materials. They improve soil quality and plant development by adding organic matter and minerals (Hue and Silva, 2000). Biomass from Medicinal and Aromatic Plants (MAPs) is rich in beneficial organic materials that can improve soil quality. As a readily available and inexpensive resource, these biomasses play an essential role in sustainable production systems, especially in organic farming (Sarkar *et al*., 2017). We will investigate organic soil amendments made from MAPs biomass waste in great detail, including mulch, charcoal, and compost.

2.7 Organic mulching- In semi-arid subtropical areas, organic mulch is essential because it reduces soil evaporation and keeps soil moisture levels up during hot summer days (Ram and Kumar, 1997). Soil moisture retention, temperature regulation, soil structure improvement, promotion of microbial communities, and enhanced nutrient availability are all positively affected by using waste biomass from Therapeutic Aromatic Plants as organic mulch, according to consistent studies. Also, according to Singh *et al*. (2001) and Patra *et al*. (1993), organic mulch can effectively limit weed growth and enhance nitrogen (N) usage efficiency by lowering ammonia volatilization. Sustainable farming operations in locations with severe climatic conditions are greatly enhanced by the varied role of MAPs waste biomass in organic mulching. Singh (2013) found that when organic mulch, such as wasted lemongrass at 7.5 t ha-1, was applied to soil, herbage increased by 16% and rosemary oil output increased by 24% compared to land without mulch. Reduced farming expenses, less pollution, and improved fertilizer N effectiveness are all benefits of this mulching method. An average of 40% yield loss in aromatic grasses was prevented by mulching with 3-7.5 t ha-1 of Java citronella distillation biomass, which effectively decreased weed infestation (Singh *et al*., 2001).

2.8 Enzyme Production- Enzymes such as cellulases, hemicelluloses, ligninases, and pectinases are produced by microbes. These enzymes are necessary for the hydrolysis of lignin-carbohydrates, which has many uses in bioprocessing, biofuel production, animal feed, and other areas. From its 2016 valuation of $5.01 billion, the worldwide enzyme manufacturing industry is projected to reach $6.32 billion in 2021. There will be a yearly growth rate of 20-30% in the Indian industrial enzyme market, which is projected to reach $361 million by 2020 (India industrial enzyme market: projection and potential, 2020). Reducing waste and pollution while simultaneously cutting production costs is possible through the use of inexpensive substrates, such as agricultural leftovers. It has proven possible to create cellulase by the dignified bioprocessing of residual biomass from Medicinal and Aromatic Plants (MAPs), including Cymbopogon winteriness and Artemisia annua. Cellulase enzymes have been successfully synthesized using this new method, which has the capacity to improve industrial and environmental sustainability while decreasing the cost of enzyme manufacturing in general (Chandra *et al*., 2009).

3. Economic Performance of Technology- The dual utilization route presents a cost-effective strategy that also delivers supplementary economic advantages to stakeholders in the Medicinal and Aromatic Plants sector. This method entails the extraction of bioactive compounds from the underutilized portions of medicinal plants and the distillation of biomass from aromatic plants, subsequently enhancing the value of the remaining biomass (Fig. 2). Integrating modern advanced technologies is essential for maximizing potential. The recycling of MAPs residual biomass is consistent with sustainable development goals within the agroindustry (Fig-3). A techno-economic assessment is essential for commercial scaling, providing guidance for capital expenditure planning, maintenance and operational cost analysis, profit estimation, and informing future research initiatives. The existing literature on cost estimation for MAP waste value addition is limited; however, this assessment is essential given the complexity of biorefinery techniques and the requirement for significant capital investments. Starch, fiber, and wax can be extracted from the residual biomass of MAPs, facilitating their application in solid fermentation and bioethanol production (Lesage-Meessen *et al*., 2018). Slavov and colleagues evaluated the techno-economic feasibility of a biorefinery utilizing lignocellulosic waste from the rose oil industry, specifically waste rose (Rosa damascena Mill.), in Bulgaria (Slavov *et al*., 2017a, 2017b).

Table 2- Bioactive chemicals derived from MAPs residual biomass.

Plant species	Bioactive compound	Waste type	Uses	Reference
Ocimum basilicum L.	Phenolic compounds such as caffeic acid and rosmarinic acid	Distillation liquid Residues	Cosmeceuticals and pharmaceutical activity	Pagano *et al.*, 2018
Citrus bergamia Risso	Flavonoid-rich	Solid biomass of distilled peel residues	Anti-microbial	Mandalari *et al.*, 2007
Santolina chamaecyparissus L.	Phenolic acids (nobiletin, dimethoxy cinnamoyl hexoxide, feruloyl-5-caffeoylquinic acid, salvianolic acid, delphinidin, quercetin-3-*O*-rutinoside)	Solid waste	Anti-oxidant	Ortiz-de Elguea-Culebras *et al.*, 2017
Hyssopus officinalis	Phenolic acids (oleoside-11-methyl ester, ferulic acid dehydrotrimer, lariciresinol derivate, cyanidin-3-rutinoside,)	Solid waste	Anti-oxidant	Ortiz-de Elguea-Culebras *et al.*, 2017
Lavandula X intermedia	Hydro-oxycinnamoylquinic acid, Phenolic acids, flavonoids, glucosides	Solid waste	Anti-oxidant	Torras-Claveria *et al.* (2007)
Poliomintha longiflora	Phenolic acids (caffeic acid, rosmarinic acid,) and volatile constitutes of essential oil (thymoquinone thymol, carvacrol, thymol acetate, methyl maleic anhydride)	Hydrosol and solid waste	Anti-oxidant & Anti-microbial	Cid-Perez *et al.*, 2019
Rosmarinus officinalis	Phenolic acids (rosmarinic, carnosic, caffeic, chlorogenic acid, and p-coumaric acids)	Solid waste	Anti-oxidant	Navarrete *et al.* (2011)
Salvia lavandulifolia	Phenolic acids (hesperidin, ferulic acid, caffeic acid, luteolin-7-*O*-rutinoside, salvianic acid, Apigenin-7-*O*-neohesperidoside, apigenin-7-*O*-glucoside, rosmarinic acid, cirsimaritin, salvianolic acid A, luteolin-7-*O* glucoronide, luteolin, salvigenin)	Solid waste	Anti-oxidant	Sanchez-Vioque *et al.*, 2018
Thyme mastichina L.	Phenolic acids (, luteolin glucoside, rosmarinic acid, quercetin glucoside quercetin, kaempferol, and luteolin)	Solid waste	Anti-oxidant	Sanchez-Vioque *et al.*, 2013
Foeniculum vulgare	Fennel oilseed by-products exhibited a remarkable antioxidant potential with high phenols and flavonoids contents	Solid waste	Anti-oxidant & Anti-microbial	Sayed Ahmad *et al.*, 2018b
Aloe barbadensis Miller	Two anthraquinones, aloesaponarin-I and aloesaponarin-II	Root	Anti-viral activity	Borges-Argaez *et al.*, 2019
Withania somnifera	Tri ethylene glycol (TEG).	Leaves	Anti-cancer Activity	Wadhwa *et al.*, 2013

The method uses a 70% ethanol solution to co-produce polyphenols and polysaccharides from discarded rose biomass, yielding an overall yield of 4.4% and 25.3%, respectively. The energy needs and average operational costs for processing waste rose biomass were established by examining the technological procedures. According to Bulgarian energy and fuel prices, the treatment of 1 kg of rose waste biomass incurs a cost of approximately 2.28 euros, while the production of 1 kg of polysaccharides and 176 g of polyphenols using this method amounts to about 9.12 euros. This method may also be applied to other biomass derived from essential oil distillation waste. Zibetti *et al*. (2013) conducted a pilot-scale simulation for the extraction of rosmarinic acid from waste of Rosmarinus officinalis, resulting in a recovery rate of 93%. The manufacturing cost for producing purified rosmarinic acid (95 kg/year) was estimated at US$ 5.85 per gram, with purification expenses comprising approximately 50% of the total cost. Sakdasri *et al*. (2019) examined the economic viability of processing lemon basil seeds without chemicals through the use of supercritical carbon dioxide in their research. The 50-L and 100-L plants exhibited optimal performance, achieving payback periods of 7.89 years and 3.92 years, respectively. The 25-L plant exhibited a lack of profitability. The initial techno-economic analysis for estimating overall capital and operational costs utilizes laboratory and small-scale experimental data, publicly available information, and considerations such as the Lang factor. These inputs may introduce significant uncertainty into the economic analysis, especially when increasing production levels.

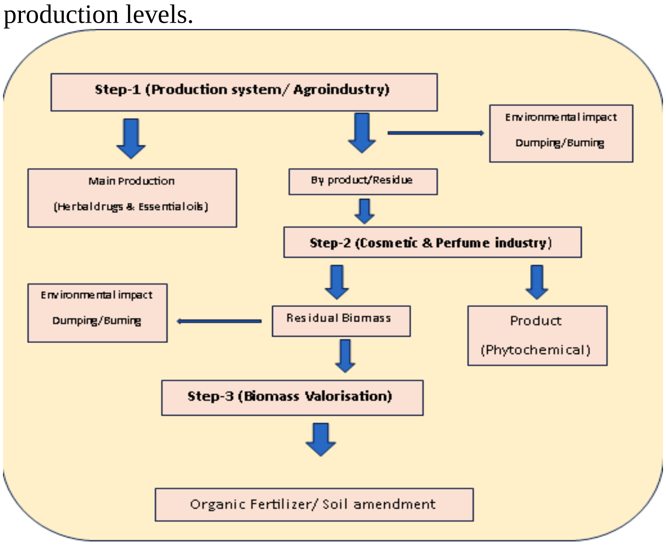

Figure 3. A Proposed Approach for Recycling MAP Leftover Biomass Addresses the Agroindustry Sector's Sustainable Development Goals (SDGs).

4. Socio-environmental Considerations- The use of residual biomass from therapeutic aromatic plants as an economical waste disposal strategy presents notable social and environmental benefits. The conversion of biomass into value-added products inherently reduces potential environmental concerns. Producing biochar results in lower greenhouse gas emissions when compared to residue burning or direct application in fields. Biochar effectively reduces NO2 emissions from agricultural soils and remediates soils contaminated with toxic heavy metals. Bio-sorbents and other value-added products contribute to the purification of wastewater and industrial effluent. Compost, biopesticides, and biochar mitigate agrochemical contamination while decreasing energy consumption and the environmental impacts linked to the production and use of chemical fertilizers and pesticides. This method is consistent with sustainable and environmentally friendly practices. Significant challenges in biomass recycling comprise insufficient infrastructure, such as engineered landfills and waste-to-energy facilities, along with a lack of skilled technical and environmental personnel proficient in managing residual biomass (Kumar *et al*., 2017). The socio-cultural background of waste management workers is significantly distinct from that of the elite class. Their occupation is frequently marginalized and associated with low social status, often involving outcast and marginalized groups in recycling activities within developing nations (Nas and Jaffe, 2004). Technical and socio-cultural barriers hinder the widespread adoption and systematic recycling of MAP residual biomass in developing countries like India. The considerable financial costs associated with proper recycling and disposal represent a notable constraint, yet these costs are warranted by the environmental challenges linked to landfilling and greenhouse gas emissions. A waste tax, for instance, imposing a charge of 1 rupee per kilogram of residual biomass, could be utilized to finance efficient recycling initiatives. The diverse physicochemical and mechanical properties of MAPs residual biomass, influenced by factors such as origin, season, region, and cultivars, present challenges in design, handling, and processing, thereby complicating the recycling process.

Conclusion

A considerable quantity of biomass, a renewable resource, is produced by the agriculture sector. The value of this biomass may be enhanced by sustainable methods and the extraction of essential phytochemicals, which can be achieved through proper management. There are monetary, ecological, and social advantages to recycling this biomass in the medicinal and aromatic plant (MAP) industry. Significant prospects exist, according to research, for the extraction of pharmaceutical-grade chemicals from residual plant components. Research out of Germany's Max Planck Institute, for example, has revealed that rose byproducts like leaves and blossoms may be transformed into bioactive phenolic antioxidants with anti-aging benefits all without breaking the bank.

MAPs include a wealth of healthful ingredients, including as polyphenolics and dietary fibers. You may speed up the synthesis of lactic acid by using techniques like ensiling lemongrass leaves with whey and sugarcane molasses. Because of their adaptability in fuel and chemical manufacturing, bio-based fuels, particularly ethanol, are seeing a rise in demand. Bioprocessed enzymes from MAPs' leftover biomass have the potential to improve sustainability while cutting costs in a number of different sectors. Sustainable development goals in agriculture are aligned with this cost-effective method of dual use.

The world's population is becoming older, and with it comes a greater interest in herbal cures, which is driving the herbal product sector, which includes cosmetics and medications, to cross $100 billion. There is an opportunity to extract useful phytochemicals from medical plants' underutilized sections and aromatic plant distillation trash. There are further financial benefits to recycling organic matter into compost, biogas, and animal feed. The majority of research on biomass's dual use has been conducted in labs, which means that there is a need for standardization before the technology can be used in industry. Maximizing advantages while minimizing environmental drawbacks should be the focus of future research, which should involve scaling up these technologies and analyzing the economic sustainability of biomass valorization.

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