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Cultivation of aromatic plant for nature-based sustainable solutions for the management of degraded/marginal lands: techno-economics and carbon dynamic

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Abstract

The cultivation of aromatic grasses on marginal/degraded land attracts attention due to their remediation potential, low input cost, and economic gain. During the distillation of these aromatic grasses, a huge amount of solid and liquid waste (hydrosol) is generated, which is not only rich in carbon content but also has a good amount of nutrient. This review summarized the potential of aromatic plants for the restoration and vaporization of distilled waste into different value-added products. In this review, estimates of the economic cost and carbon dynamics for cultivation, distillation, and waste valorisation of aromatic grasses were made using available data. Based on the literature, the available degraded land reported for India (38,600 ha) was used for the calculation. The review discussed Scientometrics analysis, the remediation potential of aromatic plants, and various routes of valorization of distilled waste generated to achieve sustainable development goals. Scientometrics analysis demonstrated the studies that include the phytoremediation potential of aromatic grasses in recent years. Among the aromatic grasses, *Chrysopogon zizanioides* (L.) Nash., *Cymbopogon flexuosus* and *Cymbopogon martini* were majorly used for reclamation purposes for dry land, mine-affected areas, and metal and pesticide-contaminated soils. The estimated profitability of the cultivation and carbon sequestration potential of these grasses in marginal/degraded land could be 22–629 million USD. Our estimations showed that the cost of carbon sequestration by the cultivation of the aromatic plant in degraded land could be 16–45 million USD. The conversion of distilled waste generated into compost, vermicompost, and biochar could sequester about 0.02 $X10^5$-335 $X10^5$ t of carbon (cost: 0.2–1913 million USD). The use of hydrosol and smoke water released during the process could sequester about 0.014 to 7403 t of carbon (cost 0.001 to 0.42 million USD). Overall the review demonstrated the sustainability and carbon footprinting of the remediation process by aromatic grasses. The review allowed the exploration of knowledge-based strategies to unlock the potential of aromatic plants for restoration and carbon sequestration, along with the value addition of distilled waste in a sustainable manner. However, more databases are needed to support the information, which includes the productivity and selectivity of individual aromatic plant for different soil and agro-climatic regions.

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Highlights

- The remediation by aromatic grasses and valorisation of distilled waste decrease the carbon foot printing.
- Estimated profitability of these grasses in marginal/degraded land could be 22-629 million USD.
- The cost of carbon sequestration by the cultivation of the aromatic plant in degraded land could be 16-45 million USD.
- The conversion of distilled waste into organic manure could sequester carbon about 0.02-335 X10^5t.
- The use of hydrosol and smoke water could sequestered the carbon about 0.014 to 7403 t.

Keywords Aromatic plants, Degraded land, Carbon sequestration, Cost economics

Graphical Abstract

1 Introduction

In recent years, the conflict between people and cultivated land has been amplified due to rapid population growth, urbanization, and industrialization, which cause serious threats to food security and health of the soil due to the excessive use of chemicals for enhancing productivity. Unfortunately, 20% of the earth's total land area was degraded between 2000 and 2015, and more than 33% of global land degradation has been reported to date resulting in a significant loss of ecosystem services offered by land systems (Fuso et al. 2019). A total of 12 million hectares of land are degraded each year worldwide (Gupta 2019). On the other side, more land is required to feed the world's population. Globally, one-fifth of land area (more than 2 billion hectares) is classified as degraded land (UNCCD 2020). The total areas of degraded and marginal land is reported is 991 Mha and 430–580 Mha, respectively (Cai et al. 2011; Berndes et al. 2003). In India, 8.12% of the total land area degraded between 2000 and 2015, and marginal land (consisting of culturable wasteland and fallow land) had an area of about 38.38 Mha in the year 2018–2019 (Vaish et al. 2016) with a low under-utilization area (Fig. 1A). Rajasthan, Jammu Kashmir, Andhra Pradesh, and Maharashtra had a higher proportion of degraded land (Fig. 1A).

Land degradation indicates a definite decline in soil performance in terms of productivity, health, strength, and environmental functions (Mahala 2020; Prince et al. 2009). Both natural and anthropogenic sources such as desertification, deforestation, cropland expansion erosion, and urbanization continuously enhance the degradation process of land worldwide (Gupta et al. 2021) and may be varied with the tropical, temperate, and arid regions (Prince et al. 2009). The natural degradation process is further catalyzed by the unsustainable use of land resources all over the world (Pacheco et al. 2018; Gerwing et al. 2022). Edaphic issues and socioeconomic conditions such as unprofitability are the major factors that restrict the utilization of these marginal lands (Jiang et al. 2019). Generally, degraded land (including marginal as well as polluted land) has low physical qualities due to variable climatic conditions, challenging soil properties, and low net productivity (Gupta et al. 2021). The lower net productivity further causes the depletion in the organic carbon content of these land. Also, the erosion processes further transport the terrestrial C pool into inland water, the atmosphere, and aquatic segments (Lal 2005). The UN has already declared the current decade (2021–2030) the 'Decade on Ecosystem Restoration', which aims to accelerate the restoration of different types of degraded lands across the world with effective and sustainable processes. The degradation of land is an irreversible process (Gibbs and Salmon 2015); hence, judicious management is required to convert it to fertile land. In addition, the reversal of land degradation at both global and local levels can contribute to the target of SDGs (UNCCD 2016). The reclamation of this unutilized land also contributes toward the SDGs set by the UN, such as (1) no poverty, (2) zero hunger, (3) good health and well-being, (11) sustainable cities and communities, (12) responsible consumption and production, (13) climate action, (14) life below water, and (15) life on land.

The net productivity and carbon dynamics are important parameters for the sustainability of the process. The restoration of these lands benefits the cultivation cultivation of high-value crops such as aromatic crops (Edrisi and Abhilash 2015), which could be a good option for marginal/contaminated lands due to their harsh nature, low input in maintenance, and economic benefits. Vetiver (*Chrysopogon zizaniodes* (L.) Nash.), lemongrass (*Cymbopogon flexuosus*), and palmarosa (*Cymbopogon martinii*) were reported previously for land reclamation purposes (Jain et al. 2020, 2022; Yadav and Khare 2023; Yadav et al. 2022; Khan and Verma 2020; and Gupta et al. 2013). For successful stabilization, various amendments such as biochar, compost, and their combination can be used (Ghosh and Maiti 2021; Mukhopadhyay et al. 2020; Ahirwal and Maitiai 2022), which not only enhance the soil quality but also increase the soil organic pool. Hence, the conversion of distilled waste into organic amendments could be a circular and carbon-negative process. The cultivation of these cash crops not only restores soil fertility and improves the soil ecosystem but also provides additional income to the farmers/land owner (Gupta et al. 2021). In addition, their cultivation in unutilized land can easily meet the demand of the aroma industries without competition with the food crops. Also, an increase in economically important secondary metabolites/oil content under stress conditions provides a further economic benefit (Mahajan et al. 2020). The essential oil extracted from these crops has a huge market in food processing, the beauty industry, aromatherapy, detergents, insect repellent, and many more (Gupta et al. 2021). The world market size for essential oils gravitated USD 7.51 billion in 2018 and is projected to reach a value of 15 billion USD by 2026 with a 9% compound annual growth rate between 2019 and 2026 (Ahuja and Singh 2019).

Previously, several studies demonstrated carbon sequestration by plantation on degraded/marginal/polluted lands. The plantation of forest can sequester 164–56 t/ha carbon during a single 41 years rotation period. However, the net carbon sink decreased from 35.95 t C/ha to 0.98 t C/ha (Lun et al. 2018). The rate of soil organic carbon sequestration was reported from 0.1 to 0.31 Mg ha^{-1} Y^{-1} in the grass and 0.7 Mg ha^{-1} Y^{-1} in forest reclamation of the mine system (Shrestha and Lal 2006). Ngo et al. (2014) found that compost and vermicompost had a positive effect on stable carbon storage. Vermicompost with biochar increased 23% soil carbon stock beyond external carbon addition. Carbon storage in soil by the addition of vermicompost may be due to high microbial activity or increased root biomass. Results of Li et al. (2021a) revealed that straw mulching increased soil organic carbon stock, soil organic carbon lability, and carbon management index in soil surface 0–20 cm. Various reviews on land restoration are available world widely (Singh and Tiwari 2022; Ahirwal and Maiti 2022; Upadhyay and Edrisi 2021; Kumar et al. 2021; Feng et al. 2019; Ait Elallem et al. 2021), however, to date, no review is available on estimating the carbon foot-printing of cultivation and processing of the aromatic crop in marginal/contaminated lands.

This review examines the techno-economic feasibility of cultivating aromatic grasses in degraded/marginal lands and the valorisation of generated waste based on available data. The review also discusses the carbon budget during the cultivation and processing of aromatic crops and value addition to generated waste. Different sections of the review cover Scientometrics analysis, techno-economic and carbon sequestration by plantation of aromatic grasses, waste valorisation and distillation, and their applications for soil and other purposes.

2 Scientometrics analysis of degraded land and their reclamation

There are various processes, such as physical, chemical, biological, and integrative methods, with different fertilization systems for improving the soil quality of degraded/marginal lands (Raj et al. 2022; Li et al. 2021b). In this review, Web of Science (WOS) and biblioshiny were used for scientometrics analysis. Using the keywords 'degraded land', a total of 7771 publications during 1990-2022 were retrieved in WOS (Fig. 1B). During these 32 years, one publication was retrieved in 1990. A rapid increase in publications was observed after 1990, with the maximum number of publications (n=925) in 2021. Among these publications, China occupies the leading position, followed by USA, Germany, Australia, India, Brazil, and England. Among these, USA, Germany, UK, and Australia were on the list of major developed countries (Fig. 1C). The Chinese Academy of Science was the most prominent institute working in this field (Fig. 1D).

The scientometrics analysis using the keywords 'degraded land', 'restoration', and 'reclamation' demonstrated 226 publications between 1981–2022 (Fig. 2A).

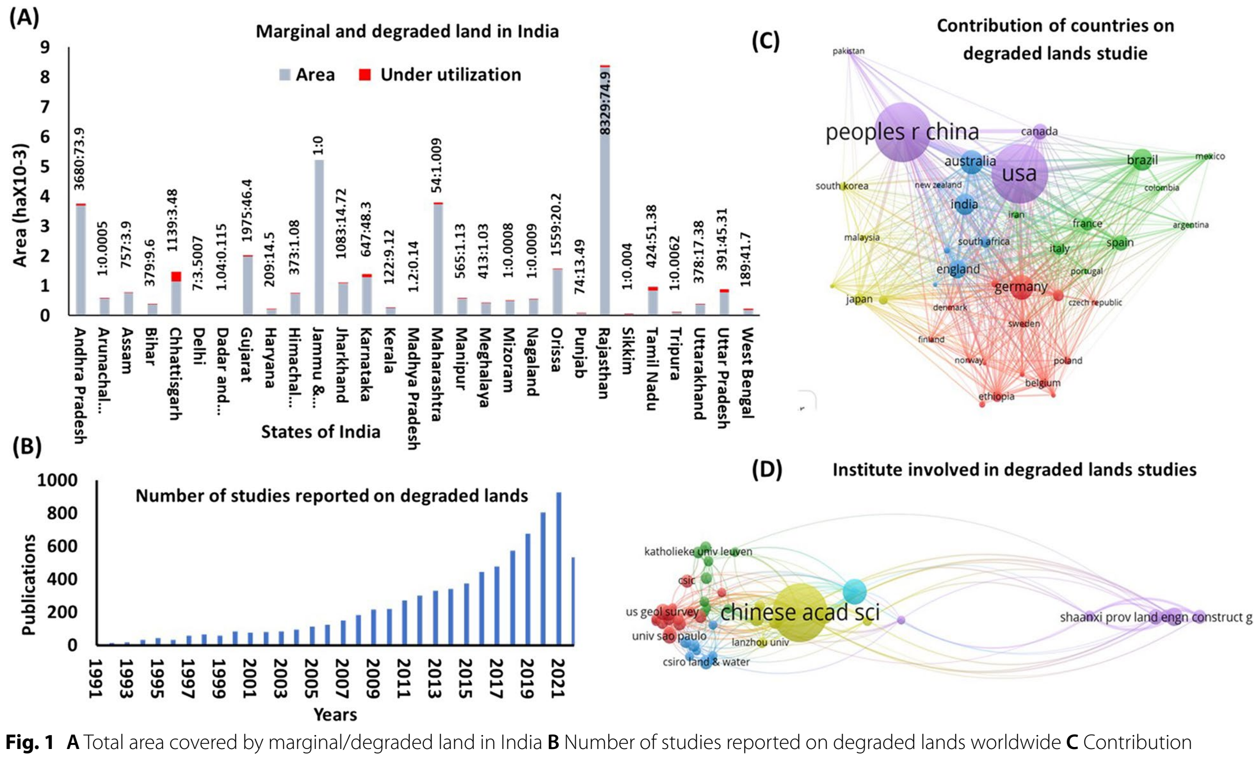

Fig. 1 **A** Total area covered by marginal/degraded land in India **B** Number of studies reported on degraded lands worldwide **C** Contribution of countries to degraded lands studies **D** Institute involved in degraded lands studies

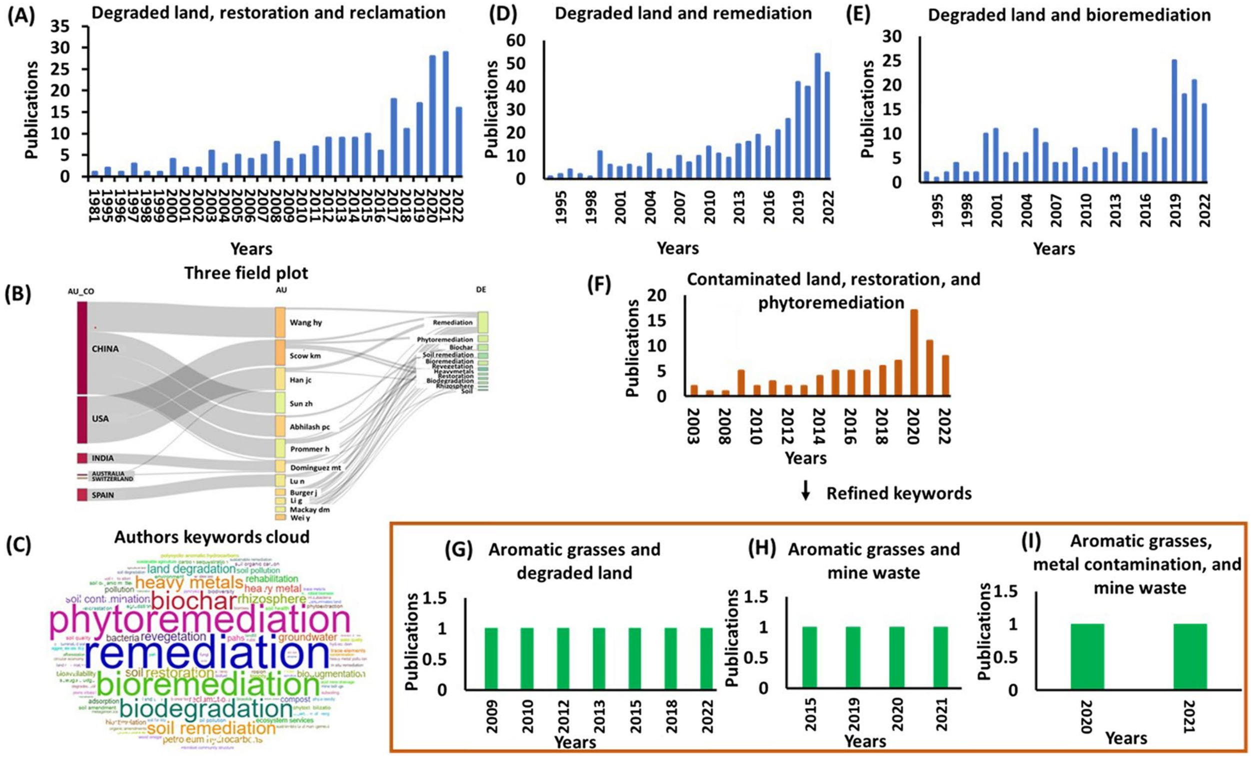

Fig. 2 Scientometrics analysis **A** With keywords: degradation land, restoration and remediation. **B** Three field plot of country, authors and keywords on restoration and remediation. **C** Authors keywords cloud. **D** Publications with keywords: degraded land and remediation. **E** Publications with keywords: degraded land and bioremediation. **F** Contaminated land, restoration, and phytoremediation. **G** Publications with keywords: aromatic grasses and degraded land. **H** Publications with keywords: aromatic grasses and mine waste. **I** Publications with keywords: aromatic grasses, metal contamination and mine waste

China is the leading country in land degradation and remediation studies, with the USA attaining 2nd and India 3rd position (Fig. 2B). The major keywords used in these studies included remediation, phytoremediation, biochar, soil remediation, bioremediation, revegetation, heavy metals, restoration, and biodegradation (Fig. 2C). However, further analysis using ’degraded land’ and ’remediation’ as keywords identified 417 publications from 1994–2022 (Fig. 2D), among which the numbers of publications among which physical, chemical, and bioremediation methods were 42, 82, and 24. Using the keywords ’degraded land’ and ’bioremediation’ retrieved a total of 225 publications from 1991–2022, with the highest number of publications (n=25) in the year 2019 (Fig. 2E). The keywords ’contaminated land’, ’restoration’, and ’phytoremediation’ identified 86 publications, with the maximum number of publications in the year 2020–2021(Fig. 2F). In this category, the keywords were further refined to three groups: 1) aromatic grass and degraded land, 2) aromatic grass and mine waste, and 3) aromatic grass and metal contamination and mine waste. The first group (Fig. 2G) demonstrated 13 publications from the year 2009–2022 from India, the USA, France, Germany, and Spain. Using the keywords ‘aromatic grasses and mine waste’ yielded 4 publications from India and Canada (Fig. 2H), while ‘aromatic grasses and metal contamination and mine waste’ identified 2 publications from Canada and Egypt (Fig. 2I). The Scientometrics analysis indicated that phytoremediation, bioremediation, and biochar were the major areas used for the restoration of degraded land. The restoration of degraded land using aromatic grasses is a recent technology and needs to be further explored more.

3 Phytoremediation potential of aromatic grasses

The highly reported technologies for land reclamation were bioremediation covers bioaugmentation, biostimulation, bioleaching, biofilters, biosorption, composting, rhizoremediation, and phytoremediation (Cristaldi et al. 2017). These processes were extensively used due to their cost-effective and non-invasive nature in comparison with other methods (Tripathi et al. 2017). Among all the bioremediation processes, phytoremediation was used to improve soil productivity and the extraction of contaminants from the soil (Tahir et al. 2016). Plants such as *Brassica juncea*, *Miscanthus*, *Eucalyptus globulus*, *Salix viminalis*, *Populus nigra* and aromatic plants such as *Cymbopogon flexuosus, Cymbopogon martinii* (Roxb. Wats), *Chrysopogon zizaniodes* (L.) Nash and *Pelargonium graveolens* (L.) were reported for successful management of the degraded/contaminated ecosystem (Table 1).

Among aromatic plants, vetiver (*Chrysopogon zizaniodes*) was reported as a tolerant crop to a wide range of abiotic stress, including salinity, sodicity, acidity, and heavy metal stress (Pandey et al. 2019). The *Cymbopogon martinii* was reported as tolerant to multiple stresses posed by acidic or mined soil (Jain et al. 2020). The ameliorative effect of *Cymbopogon flexuosus* (lemongrass) and *Cymbopogon martinii* plantation on soil enzyme activities in different dryland and mine soils were reported (Singh et al. 2021; Jain et al. 2020). *Cymbopogon citratus* was used for the accumulation of Pb^{2+} (Sobh et al. 2014), Cr^{2+}, and As^{3+} (Jha and Kumar 2017) from contaminated water. The *Cymbopogon martinii* was used for phytostabilization of tannery sludge-contaminated soil (Pandey et al. 2015). *Cymbopogon ambiguous* an Australian native grass was used for the remediation of aliphatic hydrocarbons from mine site soil (Gaskin and Bentham 2010). *Cymbopogon citratus* and *Chrysopogon zizaniodes* grasses demonstrated their potential for the phytoremediation of Cd^{2+} heavy metal (Sulastri and Sabrina 2022). Recently, *Pelargonium graveolens* L. was reported for the resilience of soil enzymatic activities in chlorpyrifos-contaminated soils (Yadav et al. 2022). Different cultivars of *Cymbopogon flexuosus, Cymbopogon martinii* (Roxb. Wats), *Cymbopogon flexuosus*, and *Chrysopogon zizaniodes* (L.) Nash had the potential to accelerate the dissipation of chlorpyrifos and its metabolite (Yadav and Khare, 2023).

4 Techno-economic and carbon dynamic during cultivation and processing of aromatic crops

For the techno-economic calculations, lemongrass, palmarosa, vetiver, citronella, and *P. graveolens* were considered and the total area for remediation referred to available degradable land in India (38600 ha). The following equations were used for the total production of aromatic crops, total oil production, and oil cost.

The following equations were used for the calculations.

$$TP = Y_B \times AA \tag{1}$$

$$TP_O = Y_O \times AA \tag{2}$$

$$TCp_O = TP_O \times RCp_O \tag{3}$$

TP = Total production
Y_B = Biomass yield of each crop (t/ha)
AA = Area available (ha)
TP_O = Total oil production
Y_O = Oil yield (Kg/ha)
TCp_O = Total oil cost (t)
RCp_O = Rate of oil cost (USD/Kg)

Net profit was calculated as

$$NP = TCp_O - TE \tag{4}$$

NP = Net profit
TE = Total expenditure

Biomass yield (t/ha), oil yield (Kg/ha), oil cost (USD/kg), and expenditure of aromatic plants cultivation and harvest (USD/ha) were taken from the Central Institute of Medicinal and Aromatic Plants (Aush Gyanya 2021) (Table 2). The expenditure cost included the cost of planting material, labour, fertilizer, and transportation.

The estimated expenditure for the cultivation of the aromatic plant in all available marginal lands in India and produced oil costs were 11 to 36 million USD and 41 to 1729 million USD, respectively, which could provide a net benefit of 22–629 million USD (Table 2). In addition, the cultivation of the aromatic plant in degraded land also reduces carbon loss during the weathering process. Generally, the erosion process and low input of biomass carbon cause a negative carbon budget in degraded lands (Lal 2010). Total soil organic carbon loss due to land degradation was reported up to 8–12 Mg C/ha (Swift et al. 1994). However, in the current scenario, the annual global emissions of CO_2 in the first decade of the twenty-first century were reported as 3.6–4.4 Pg (petagrams or billion tonnes), representing 10 to 12% of the current global carbon emissions (Prăvălie 2021).

The transportation cost of the biomass for distillation was calculated using the capacity of a vehicle 15 t and distance traveled 10 to 25 km with transportation cost taken as 7.5 (for 10 km) to 18.75 (25 km) USD /Km and C emission during the transportation was taken as 125, and 133 g/km (Jana and De 2015). The total expenses on transportation of planting material for distillation after harvest could be 0.05 to 1.93 million USD, while carbon emission during transportation could be 9 to 342 t. During the distillation process, wood was used as fuel, and 100–200 kg of wood is required for 100 tonnes, and the C released rate of wood burning was taken as 337.5 g C/Kg and 480 g C/kg (Singh et al. 2019; Johnson 2023). CO_2 estimation from wood burning was calculated as

$$WR = \frac{B_{AD}}{B_{CD}} \tag{5}$$

WR = Wood requirement
B_{AD} = Total biomass available for distillation (t)

Table 1 Various plants used for restoration of degraded, contaminated and marginal lands

S.No	Area	Plant spp.	Potential application	References
1	Uttar Pradesh, India	*Vetiveria zizanioides, Cymbopogon citratus, Cymbopogon martinii,* and *Cymbopogon winterianus*	Biomass production, soil reclamation potential of plant spp. [marginal land with slightly alkaline soil]	Maddhesiya et al. 2021
2	Mediterranean region	*Miscanthus giganteus, Arundo donax* L., *Panicum virgatum* L. and *Cynara cardunculus* L	Biomass production for stationary heat and power generation. [marginal land]	Schmidt et al. 2015
3	Italy	*Saccharum spontaneum* L. spp. *aegyptiacum* (Willd.) Hack	Biomass yield, biomass quality, physiological efficiency at different soil water availability [affected by severe drought]	Cosentino et al. 2015
4	Province of Soria, Spain	*Populus euramericana*, *Salix matsudana* x *Salix* spp., *Platanus hybrida*, and *Robinia pseudoacacia*	Biomass production and fuel quality [low P and K content and low water and nutrient capacity of soil]	Fernández et al. 2020
5	Yellow River Delta, China	*Miscanthus* genotypes And *Panicum virgatum* L	Biomass yield and quality (cellulose, hemicellulose, lignin and ash) for the bioenergy industry [marginal land with sline-alkaline soil]	Zheng et al. 2019
6	Nebraska, US	*Panicum virgatum* L., *Miscanthus giganteus*	Biomass feedstock production for bioenergy [Poorly drained, frequently flooded and nitrate contaimination]	Gopalakrishnan et al. 2011
7	Çukurova, Turkey	*Mentha arvensis*	Agronomic and chemical responses of *M. arvensis* to different planting seasons [high line and low carbon, inefficient alluvium]	Soltanbeigi A, Özgüven M 2021; Soltanbeigi et al. 2021
10	Hills of Latium Region	*Cynara cardunculus* L. var. *altilis* DC) and wild (*Cynara cardunculus* L. var. *sylvestris* Lam)	Comparison of yield potential of cultivated and wild genotypes, quality of lignocellulosic biomass and grain [rainfed conditions]	Francaviglia et al. 2016
13	India	Palmarosa	Restore mine waste soil, metal immobilization, improve microbial activities and nutrient mineralization [highly acidic soil with meal contamination]	Jain et al. 2020
14	India	*Pelargonium graveolens*	Remediation of contaminated highly acidic spoil [highly acidic soil with meal contamination]	Jain et al. 2022
15	India	*Cymbopogon flexuosus*	Improve soil enzymatic activity, increase microbial density, high abundance of microbes involved in carbon metabolism [rain-fed conditions]	Singh et al. 2021
16	Iran	*Launaea arborescens*(Batt.) Murb, *Artemisia santolina* Schrenk, *Pulicaria gnaphalodes* (Vent.) Boiss, *Zygophyllum eurypterum* Boiss. & Buhse, *Peganum harmala* L., *Pteropyrum olivieri* Jaub. & Spach, and *Aerva javanica* (Burm. f.) Juss. ex Schult	Biomass used for hyperaccumulation and phytostabilization of heavy metals [Cu, Zn, Cd, and Pb]	Mousavi Kouhi and Moudi 2020
17	India	*P. graveolens*	Biochar amendment and soil enzymatic resilience [chlorpyrifos contaminated soils]	Yadav et al. 2022
18	India	*Cymbopogon martinii* (Roxb. Wats), *Cymbopogon flexuosus*, and *Chrysopogon zizaniodes* (L.) Nash [different cultivars]	Dissipation of chlorpyrifos and 3,5,6 trichloro-2-pyridinol [chlorpyrifos contaminated soils]	Yadav and Khare 2023

$B_{CD=}$ Biomass used for distillation per batch (t)

$$C_w = WR \times C_D \tag{6}$$

C_W = Carbon released due to wood burning (t)
C_D = Carbon released due to wood burning (t)

The total carbon released during the distillation could be 35 to 1482 t. The total cost of C emission during distillation (transportation + wood burning) could be in the range of 0.002 to 0.104 million USD (Table 2).

The mean carbon sequestration by the cultivation of lemongrass, palmarosa, and vetiver was 5.38, 6.1, and 15.2 t/ha in biomass and 3.08, 2.79, and 5.75 t/ha in soil, respectively (Khan and Verma 2020). The carbon cost was taken as \$51–57/t (Struhs et al. 2020). These values were used for the calculation of total carbon sequestration by the cultivation of these plants. No data was available for citronella and *P.graveolens*; hence lowest values were taken for the calculation in the present study. Carbon sequestration by biomass (BCseq) and by soil (SCseq) were calculated as

$$BCseq = AA \times C_{BSeq} \tag{7}$$

$$SCeq = AA \times C_{SSeq} \tag{8}$$

BC_{Seq} = Carbon sequestration by biomass
SC_{Seq} = Carbon sequestration by soil
C_{BSeq} = Carbon sequestration in biomass (t/ha)
C_{CSeq} = Carbon sequestration in soil (t/ha)
AA = Area available (ha)

Hence, the cultivation of aromatic grasses can sequester carbon from 20.77 to 58.82×10^4 t carbon in biomass and 10.77 to 22.18×10^4 tonne C in soil, which could cost about 16.1 to 44.9 million USD (Table 2).

5 Valorization of waste generated after distillation of aromatic grass

Though the cultivation of aromatic plants in unutilized lands provides many benefits, such as remediation of lands, carbon sequestration, and soil quality improvement, but the generation of vast waste material in the form of solid biomass or liquid spent after the extraction of essential oil needs to be addressed for the sustainability of the process (Yarin et al. 2022). Only 0.5–10% of total fresh biomass may be used during distillation, and the rest of the waste is dumped or burnt. All over the world, approximately 20 million tonnes of dry biomass are produced every year after distillation, while India contributes 3 million tonnes of solid biomass every year (Basak et al. 2021; Sayed-Ahmad et al. 2017a, b). Distillation residue can be classified into three categories- wastewater, hydrosol, and solid residue. In India, generated wastewater is directly recycled for distillation and then used for agricultural purposes, and no study has been reported on the usage of waste water. However, the conversion of hydrosol and solid-distilled biomasses (DW) into value-added products has been reported by several authors.

5.1 Hydrosol

The spent water, known as hydrosol, is produced due to the condensation of water vapours in the collecting chamber during the distillation process (Yarin et al. 2022), which could be used for various purposes (Fig. 3A). It consists of some fractions of essential oil and aromatic compounds along with components like alcohol, ketone, phenol, ether, and esters (Inouye 2008). The presence of constituents in rose oil, i.e., 2-phenyl ethanol, was reported in hydrosol as well (Zhu et al. 2012). Sage hydrosol obtained from the fresh herb of sage during steam distillation is rich in camphor (43.38%), a major constituent of sage oil (Baydar et al. 2013). The *Ocimum basilicum* hydrosol is a rich source of a compound such as linalool (66.5%), eugenol (18.9%), and eucalyptol (7.1%) (Traka et al. 2018). Likewise, hydrosol obtained from citronella and rose contains an abundant amount of terpenoids known for the reduction in enzymatic activity of phenylalanine ammonia-lyase, peroxidase, and polyphenol oxidase and reported as an anti-browning agent for fresh-cut fruits (Xiao et al. 2020). The hydrosol of basil enhances the seed germination rate and affects shoot and root length in basil and quinoa (Camlica et al. 2017). *Origanum* sp. hydrosol may act as a natural preservative and act as a good alternative for the storage and preservation of fresh-cut vegetables under optimal storage conditions. Aqueous extracts are more effective than essential oil in inhibiting polyphenol oxidase activity (Tanhaş et al. 2020). The use of these hydrosols as a source of antibacterial activity (Hussien et al. 2011; Verma et al. 2016; Acheampong et al. 2015), antifungal activity (Verma et al. 2016; Franzener et al. 2007; Belabbes et al. 2017) and pesticidal activity (Zhu et al. 2012) is reported in the literature. Hydrosol of lemongrass is used as the local source for the production of different types of paints (mat, screeding, emulsion, and gloss) and is also a supplement for broiler chicken (Rabadan 2022). The utilization of hydrosol for these purposes not only improves the product quality but also sequesters the carbon which otherwise wastes. The reduction in carbon footprinting due to the application of hydrosol was calculated.

$$TCS_H = B_{CD} \times RP_H \times C_H \tag{9}$$

TCS_H = Total C save in hydrosol
B_{CD} = Biomass used for distillation per batch (t)
RP_H = Hydrosol production rate (L/t)

Table 2 Estimation of production cost, carbon emissions and Cseq by cultivation of aromatic plant on degraded/marginal lands of India

	Crop	Biomass yield (t/ha)[a]	Oil yield (Kg/ha)[a]	Area available (ha)	Total production (t)	Total oil production (t)	oil cost (USD/kg)		Expenditure (USD/ha)		Total oil cost (Million USD)		Total expenditure (Million USD)		Net profit (Million USD)		
															A	B	C
Production	Lemongrass	30	2240	38,600	1,158,000	86,464	8	20	288	500	648	1729	11	19	637	1710	629
	Palmarosa	40	225	38,600	1,544,000	8685	18	18	375	500	152	152	14	19	138	133	133
	Vetiver	2.7	33	38,600	104,220	1273	150	188	938	938	191	239	36	36	155	203	155
	Citronella	21.5	285	38,600	829,900	11,001	4	10	313	500	41	110	12	19	29	91	22
	P. graveolens	29.7	59.6	38,600	1,146,420	2300	125	150	1000	1000	288	345	39	39	249	306	249
C emission	**Crop**	**Total production (t)**	**Waste generated (t)**	**Transportation cost and C emission**					**Carbon emission due to distillation**				**Cost economics**				
				Transportation frequency[b]	**Transportation cost (Million USD)**		**Carbon emission (t)**		**Wood required (Kg)**		**Carbon emission (t)**		**Total C emission (t)**		**Carbon price (Million USD)**		
					For 10 km	**For 25 km**			**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	
	Lemongrass	1,158,000	1,042,200	77,200	0.58	1.45	97	257	1,158,000	2,316,000	391	1112	487	1368	0.025	0.078	
	Palmarosa	1,544,000	1,389,600	102,933	0.77	1.93	129	342	1,544,000	3,088,000	521	1482	650	1824	0.033	0.104	
	Vetiver	104,220	93,798	6948	0.05	0.13	9	23	104,220	208,440	35	100	44	123	0.002	0.007	
	Citronella	829,900	746,910	55,326	0.41	1.04	69	184	829,900	1,659,800	280	797	349	981	0.018	0.056	
	P. graveolens	1,146,420	1,031,778	76,428	0.57	1.43	96	254	1,146,420	2,292,840	387	1101	482	1355	0.025	0.077	
C Seq	**Crop**	**Area available (ha)**	**[b]Cseq (t/ha) in biomass**	**[b]Cseq (t/ha) in soil**	**Total Cseq by biomass (BCseq) in t**	**Total Cseq by Soil (SCseq) in t**	**BCseq cost (Million USD)**		**SCseq cost (Million USD)**		**Total Cseq cost (Million USD)**						
	Lemongrass	38,600	5.38	3.08	207,668	118,888	10.6	12.8	6.1	6.8	16.6	18.6					
	Palmarosa	38,600	6.1	2.79	237,004	107,694	12.1	13.5	5.5	5.5	17.5	19					
	Vetiver	38,600	15.2	5.75	588,264	221,950	30	33.5	11.3	11.3	41.3	44.9					
	Citronella	38,600	5.38	2.79	207,668	107,694	10.6	11.8	5.5	5.5	16.1	17. 3					
	P.graveolens	38,600	5.38	2.79	207,668	107,694	10.6	11.8	5.5	5.5	16.1	17.3					

A: calculation made by minimum value of cost-minimum value of expenditure

B: calculation made by maximum value of cost-maximum value of expenditure

C: calculation made by minimum value of cost-maximum value of expenditure

[a] Biomass yield and cost taken from Aush Gyanya 2021

[b] Cseq (t/ha) from Khan et al. 2020; Jana and De 2015, Carbon costs: 51 to 57 USD/t taken from Struhs et al. 2020, Capacity of the vehicles (15 t) and transportation cost taken as 7.5 (for 10 km) to 18.75 (25 km) USD /Km and C emission was taken as 125 and 133 g/km (Jana and De 2015 and Swift et al. 1994). Metadata used from above mentioned studies with total number of samples 19 in trplicate

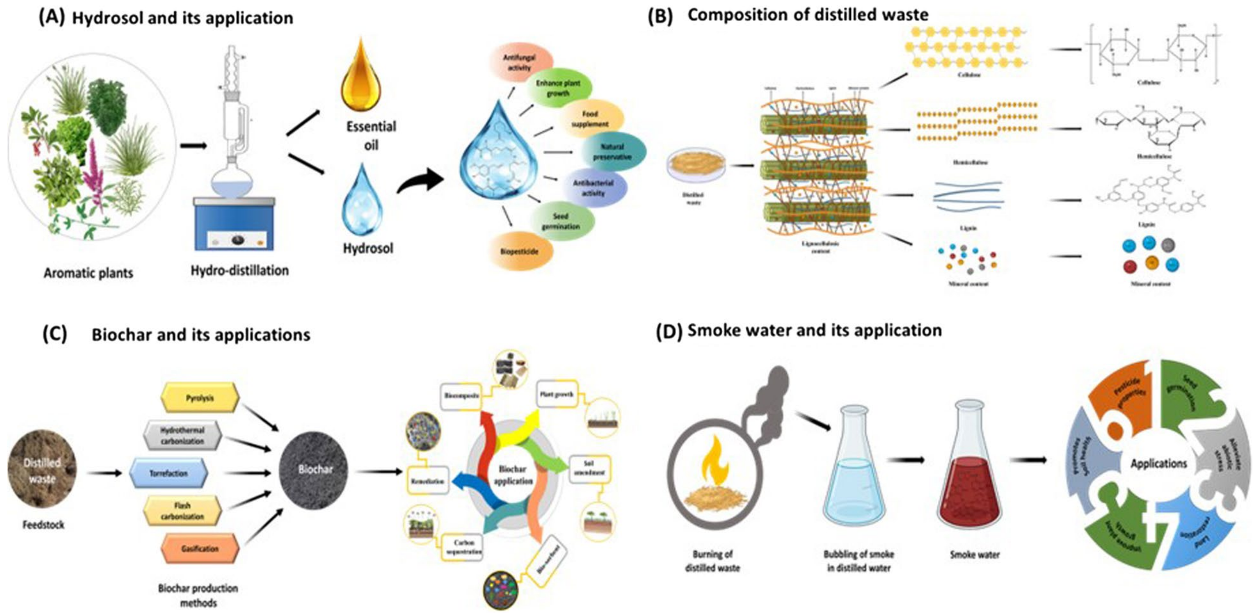

Fig. 3 **A** Hydrosol and its application **B** Composition of distilled waste **C** Biochar and its applications **D** Smoke water and its application

C_H = Carbon content of hydrosol (mg/L)

The reported hydrosol production rate in the literature is 4.7 L/Kg (Francezon and Stevanovic 2018). The carbon content of hydrosol is reported as 200 to 1000 mg/L. The use of hydrosol for agricultural purposes can save carbon (100 to 7403 t carbon). This will save a cost of 0.01 to 0.42 million USD on using hydrosol (Supplementary 4). However, carbon and energy savings due to the replacement of similar technologies with hydrosols need to be addressed in the future.

5.2 Solid distilled baggage

As reported earlier that due to low oil content (< 5% oil yield) in aromatic plants, a huge amount of biomass is left after distillation (Boruah et al. 2019; Wany et al. 2014; Saha et al. 2018). For example, the total production of citronella oil is 5000 tons on an annual basis (Kumoro et al. 2021), and the plant contains only 1% of essential oil. Likewise, the leaves of *Cymbopogon nadrus* consist of 1–2% essential oils (Katiyar et al. 2011). Palmarosa oil production in India is 15 metric tons from both cultivated and natural resources with 0.1–0.4% essential oil yield (Saha et al. 2018). China and Indonesia are the chief producers of lemongrass oil, accounting for 40% of the world's production, which is estimated to be between 800 and 1300 tons of oil per year. In India, the total aromatic spent residue produced is 6 million tons on an annual basis (Singh 2013; Rout et al. 2015) from the distillation of *Mentha*, lemongrass, palmarosa, and citronella.

The composition of solid distilled wastes (DW) varied with plant types (Fig. 3B) and is also according to climate and area of cultivation. However, irrespective of theses, DW consists of large amounts of organic materials like cellulose, carbohydrates, and minerals. DW is also rich in carbon (36–40%) and mineral contents (Ahsan et al. 2022). DW of *Cymbopogon flexuosus* contained 37% carbon, 5% hydrogen, 2% nitrogen, and 53% ash content (Deshmukh et al. 2015). The presence of 72.13 ± 0.5% holo-cellulose, 44.16 ± 0.32% α-cellulose, and 17.39 ± 0.34% lignin in DW of lemongrass was reported by Kaur and Dutt (2013), while the presence of 35 ± 1.4% cellulose, 32 ± 1.5% hemicellulose, and 13 ± 1.3% lignin in DW of lemongrass was reported by Mishra et al. (2018a). However, the DW of *Ocimum* and *Mentha* contained 31% and 33% cellulose, 19% and 22% hemicelluloses, and 42% and 31% lignin, respectively. Due to the high carbon content and presence of minerals, the conversion of DW in mulch, vermicompost, and biochar for soil amendments was preferred in some studies (Supplementary 5). However, the isolation of high-value materials (nanocellulose, adsorbent, etc.) and their application in medical and environmental fields were reported in some studies (Supplementary 5).

6 Recycling of distilled waste for soil application

Most of the studies reported that the conversion of distillation waste into organic mulch, compost, and biochar not only sequesters carbon and mineral but also improves the soil quality and plant yield (Jain et al. 2017;

Yadav et al. 2019a; Nigam et al. 2019a). Their application in soil reduces the load of synthetic and could be an efficient nutrient management strategy.

6.1 Organic mulching and compost

Organic mulch and compost are rich in carbon content as well as nutrient content. The palmarosa mulch consisted of 26.3% C, 1.33% N, 4.93% available K, and 0.93% total K (Basak 2018). DW-derived mulch had 32% water holding capacity, 0.62 g/m^3 bulk density, 26.8% C, and 2112 mg/kg P (Yadav et al. 2019b). The application of mulch/compost in soil enhances its quality, nutrient availability, microbial activities, and herbage (Singh et al. 2001; Singh 2013). The mulch of DW of citronella and Japanese mint conserved the soil moisture content (2–4%) and improved the nitrogen fertilizer use efficiency of the plant (Ahmad et al. 2007). Similarly, compost of DW of palmarosa was reported as promising K-enriched compost, which can reduce dependency on chemical fertilizers in an economical manner (Basak 2018). Mulch derived from *Mentha* and lemongrass enhanced the plant growth and reduction in metal uptake (Yadav et al. 2019b; Nigam et al. 2019b, 2021). A study reported that the application of FYM in cucumber provided a net profit of $ 5394/ha as compared to the unamended soil ($2669/ha) (Apori et al. 2021). The carbon sequestration potential of mulch in soil was reported as 4.73–7.88 t/ha (Yadav et al. 2019a) at an application rate of 2.5 to 5 t/ha (Wang et al. 2021).

For the calculation of the techno-economic and carbon sequestration potential of mulch in soil, DW generated was taken as 10% lower than the total biomass used for distillation, assuming loss in biomass during the distillation process. The following equations were used.

$$AC = \frac{TWS}{RA_M} \tag{10}$$

AC = Area cover (ha)
TWS = Total waste generated (t)
RA_M = Application rate of mulch (t/ha)

$$TC_{Seq} = AC \times MC_{Seq} \tag{11}$$

TC_{Seq} = Total carbon sequestration (t)
AC = Area cover (ha)
MC_{Seq} = Carbon sequestration potential of mulch (t/ha)

A total of 14.78 to 262.9 × 10^4 tonnes C is sequestered in this process, which costs about 9 to 134 million USD (Supplementary 6). However, mulching is a general practice, but data on the characteristics of distilled waste-derived mulching and its impact on soil and plant is limited.

6.2 Vermicompost

Vermicompost (VM) is a technique of non-thermophilic decomposition of any organic matter with the help of mutual interaction between earthworms and microbes (Mainoo 2009). VM is also rich in carbon and nutrient contents. VM prepared by utilization of distilled waste of *Mentha* and citronella acts as a nutrient supplement to plants for better growth and to reduce root-knot infection in plants (Pandey et al. 2010). The presence of 22.6% carbon, 1.8% nitrogen, 0.22% phosphorus, and 0.73% potassium was reported in vermicompost from DW (Singh et al. 2013). Vermicomposting of DW of citronella plant (*Cymbopogon winterianus* Jowitt.) consisted of 827 g/kg ash, 109 g/kg TOC, 571 mg/kg available phosphorus, and 974 mg/kg potassium (Deka et al. 2011). Distilled waste-derived VM had a bulk density of 0.60 g/m^3, a water holding capacity of 28%, carbon content of 24.1%, and total phosphorus of 1149 mg/kg (Yadav et al. 2019b).

The VM from citronella bagasse and paper mill sludge enhanced the nutrient profile and increased the beneficial bacterial community in the soil (Boruah et al. 2019). Distilled waste-derived vermicompost increased the yield of geranium biomass (1.73–2%) and nitrogen use efficiency (1.4–3.8%) (Yadav et al. 2019c). The distilled waste-derived VM improved the herbage yield of *Withania sominifera* by 48% in metal-contaminated soil (320 ppm Pb + 15 ppm Cd) at the application rate of 1 tonne/hectare with a reduction in metal uptake (Nigam et al. 2019c). Vermicompost from distillation waste of geranium and *Ocimum* doubled the productivity of Patchouli (*Pogostemon cablin* (Blanco) Benth) (Singh et al. 2015). However, the addition of VM in soil alone was profitable in terms of productivity and reduction in nitrogen and phosphorus losses, but it could be unprofitable when added with NPK due to more nutrient loss as compared to productivity (Yadav et al. 2019a). VM yield and production cost were reported as 40–50% and 100–750 mg in 16 kg of biomass (Ramnarain et al. 2019). The cost of production of VM was reported as 18.75 USD/t (Devkota et al. 2014). However, VM application sequestered C in the soil at the rate of 0.585 t ha^{-1} (Naikwade 2019).

Using these values, the total production cost of VM and Cseq potential were calculated as follows:

$$AC = \frac{TWS}{RA_V} \tag{12}$$

AC = Area cover (ha)
TWS = Total waste generated (t)
RA_V = Application rate of vermicompost (t/ha)

$$TC_{Seq}=AC \times VC_{Seq} \tag{13}$$

TC_{Seq} = Total carbon sequestration (t)
AC = Area cover (ha)
VC_{Seq} = Carbon sequestration potential of vermicompost (t/ha)

Estimation demonstrated that the total production cost of VM could be 1 to 13 million USD for the waste generated from the aromatic grasses' cultivation in degraded land. The total Cseq was 0.4 to 4.06×10^4 t, which cost about 0.2 to 3.3 million USD (Supplementary 6). The cost of Cseq was less than that of the VM production because the cost of improvement in soil properties and plant yield was not included (Supplementary 6).

6.3 Biochar and smoke water

The yield of the biochar from distilled waste varied with the temperature and feedstock used. The yield of distilled waste-derived biochar varied from 35–50% (Singh et al. 2015). The cost of biochar production also depends upon the technique used. For example, Meyer et al. (2011), reported the 560 USD/t production cost of biochar using fast pyrolysis methods. At the same time, Spokas et al. (2012) reported 246 USD/t as the production cost of biochar by the slow pyrolysis method. The production costs of biochar using a kiln and farm-available distillation units were reported as 77 and 83 USD/t, respectively (Ahsan et al. 2022; Shamim et al. 2015). According to these values, conversion of all waste into biochar will cost from 7 million USD to 778 USD depending upon the method used and plant used for cultivation (Table 5). The selling cost of biochar in the market was reported as $2650–8850 (Ahmed et al. 2016). The total selling price of biochar prepared will be 87 to 6149 million USD (Table 5). Hence, the production of biochar could also be profitable. However, biochar is considered to be able to sequester C in soil for the long term, reduce GHG emissions and also reduce the C footprint by replacing fertilizers. The metal-data analysis demonstrated (Budai et al. 2013) that biochar with $H/C > 4$ sequestered 50% of its carbon, and biochar having $H/C < 4$ sequestered 70% of its carbon for 100 years. Hence, the carbon sequestration potential (CSP) of biochar will range from 50 to 70% of its carbon content. Hence, Cseq by biochar produced can be calculated as indicated by Ahsan et al. (2022).

$$B_rC_{Seq} = C_B \times \frac{PB_rC_{Seq}}{100} \times TB_r \tag{14}$$

B_rC_{Seq} = Carbon sequestration by biochar
C_B = Carbon content of biochar (%)
PB_rC_{Seq} = Carbon sequestration potential of biochar
TB_r = Total biochar (t)

The estimated yearly carbon sequestration by biochar used for soil application could be 93.56×10^4 to 336×10^5 tones from the distilled waste generated. This will cost about 48 to 1913 million USD (Supplementary 10). The reduction in GHG emission from biochar amendment was reported as 0.51–1.52 t CO^2/ha (Ji et al. 2018). Hence, total GHG reduction by biochar application in soil could be 3349 to105610 t CO^2/ha, which costs 0.2 to 6 million USD at 5 and 10 t/ha application rate of biochar (Supplementary 10).

The cost of fertilizer replacement (Cp_{FR}) by biochar was calculated using the following Eq.

$$Cp_{FR} = FR - TB_r \times Cp_S \tag{15}$$

Where FR (fertilizer replacement by biochar) and Cp_S (saving cost) were taken as 3.9–6.1 kg t^{-1} and $ 0.53 -1.48 per t, respectively (Field et al. 2013). The cost of fertilization replacement by biochar amendment in soil could be 0.08 to 6.27 million USD (Supplementary 10).

Pyrolysis of biomass for biochar production generated several gases and smoke, which had deleterious effects on human health and contributed to anthropogenic-driven climatic change. These gases and smoke can be repurposed for biofuel production (Vamvuka 2011) and alternatively applied in agricultural practices for the improvement of crop yield in the form of smoke water (Kulkarni et al. 2011) (Fig. 3D). The different production temperatures and compositions of smoke water were reported in the literature. Smoke water was prepared by bubbling smoke in distilled water to dissolve active biological compounds (De Lange and Boucher 1990). As the smoke solution prepared by the combustion of lignin, cellulose, hemicellulose, and other carbon compounds in plant materials, it contained more than 4000 chemical compounds, including phenolic compounds (guaiacol and syringol), alcohol, aldehydes, ketones, and organic acids such as furfural, formaldehyde, carboxylic and acetic acid that act as antioxidants, antiseptics, and antibacteria (Dogrusoz 2022). The yield of liquid smoke from dried biomass water hyacinth was obtained at 0.2 mL per 100 g, 12.3 mL per 100 g, and 16.3 mL per 100 g at a temperature of 117 °C, 400 °C and 683 °C, respectively (Ratnani et al. 2021). The smoke water production from different biomass, application rate, and utilization reported in various studies is given in (Table 3). Sparg et al. (2006) evaluated the effect of both smoke aerosol and smoke solution on commercially cultivated maize seeds (Z. mays cv. PAN6479). *Cymbopogon jwarancusa* smoke extracts (1:100 and 1:400 v/v) improved germination in saline conditions via regulating redox homeostasis as well as modulating stress regulatory gene expression, which were reported previously (Hayat et al.

2021; Waheed et al. 2016). Similarly, the combined effect of plant growth-promoting bacteria *Bacillus safensis* and plant-derived smoke *Cymbopogon jwarancusa* under salinity has a priming effect (Khan et al. 2017). The smoke solution prepared from *Cymbopogon jwarancusa* has been used successfully to reduce plant uptake of toxic heavy metals from soils, such as Pb (Akhtar et al. 2017). Similarly, smoke water reduced boron toxicity (Çatav et al. 2021; Pirzada et al. 2014; Küçükakyüz and Çatav 2021). Smoke water consists of organic acids, phenolic compounds, sugar, and acids of sugar that can form a complex with boric acid to restrict the uptake of boron (Hu and Brown 1997). It also revealed that the activity of antioxidant enzymes increases a significant 2.65-fold increase was in peroxidase activity. Generally, all plant materials can be used as a source to produce smoke water extract (Miwa and Fujiwara 2010; Jäger et al. 1996). Flematti et al. (2004) have reported and identified a compound in smoke produced from cellulose-containing compounds or any plant material which is similar to the compound present in plant-derived smoke water, which is responsible for seed germination. Smoke water could be made from a wide range of sources such as trees- *Crataegus pinnatifida* and *Magnolia denudate*, Lemon eucalyptus, *Acacia nilotica* (Zhou et al. 2018; Elsadek and Yousef 2019; Sajjad et al. 2014), herbs- white willow, sage, rosemary (Elsadek and Yousef 2019), perennial grasses- *Cymbopogon jwarancusa*, the litter of alfalfa (Bonanomi et al. 2021) and dry litter of lawn grass mixture of *Festuca rubra* and *Lolium perenne* (Mojzes and Kalapos 2014), crop residue- rice straw (Elsadek and Yousef 2019), cellulose, wood sawdust, and olive mill residue (Bonanomi et al. 2021). There is no literature available with details on the use of distilled waste for the production of smoke water.

The primary compound responsible for the germination process was identified as 3-methyl-2H-furo[2,3-c] pyran-2-one (1, karrikinolide) (Van Staden et al. 2004; Flematti et al. 2004), which has introduced a class of plant bioactive compounds that are called karrikins (Nelson et al. 2009) and are considered to be a new and vital family of naturally occurring phytohormones (Light et al. 2009; Chiwocha et al. 2009). Hence, it could cause an increase in plant growth. The smoke water application (0.1 to 0.2%) enhanced germination in papaya (22–24%) and fruit (20–35%) and biomass (9–25%) in tomatoes, with a net gain of $329 (Govindaraj et al. 2016). Smoke water could act as a biostimulant for achieving viable and nutritionally superior yields (Ngoroyemoto et al. 2019). The carbon content of smoke water prepared during biochar production of nutshell and date seeds was 50–61 g/L with a yield of 333 L/t and also had a sufficient amount of nutrients such as Ca, Mg, Fe, N, P, Zn, NH_4 and NO_3. It enhanced the lettuce germination up to 28–29% (Abdelhafez et al. 2021). Results of Harti et al. (2020) also indicated that liquid smoke produced from the combustion of cocoa pod husk improved the growth potential and seed germination of red chili seeds. Probably, smoking gases regulate reactive oxygen species (Aslam et al. 2019). Hence, the addition of smoke water could not only reduce the carbon footprint of the process during pyrolysis but also improve plant productivity. The carbon-saving cost from smoke water was calculated as

$$TP_{Sw} = WS_{Py} \times RP_{SW} \tag{16}$$

TP_{SW}= Total smoke water production (L)
WS_{P_y}= Waste used for pyrolysis (t)
RP_{SW}= Rate of smoke water production (L/t)

$$TCS_{SW} = TP_{SW} \times C_{SW} \tag{17}$$

TCS_{SW}= Total carbon saving (Kg)
$TP_{SW=}$ Total smoke water production (L)
C_{SW}= Carbon content in smoke water (g/L)

$$CSCp = TCS \times CCp \tag{18}$$

$CSCp$= Carbon saving cost (Million USD)
TCS= Total carbon saving
CCp= Carbon cost (USD)

It was observed from the above calculation that biomass waste could produce 281–4172 L of smoke water, which saved 14.1–255 kg of C, costing 0.001–0.016 million USD (Table 4). These values are added to the improvement of seed quality.

7 Other applications of distilled waste

Besides the use of waste biomass for soil amendments, the use of distilled waste for other applications and in the production and isolation of high-valued chemical waste such as fuels, biosorbents, animal feed, cellulose, nano cellulose, and glucose was also reported in various studies.

Bio-coal prepared from *Cymbopogon flexuosus* and *Vetiveria zizanioides* after oil extraction demonstrated good calorific values, and blending of these with high sulphur sub-bituminous coal can reduce SO_2 emission (Yadav et al. 2013). However, no other data is available on the fuel properties of distilled waste, and this needs to be explored.

Zuo et al. (2012) reported that lemongrass immersed in NaOH solution was an effective bio-sorbent for single as well as multi-metal sorption (maximum sorption of 13.93 mg/g Cu, 15.87 mg/g Zn and 39.53 mg/g Cd). Activated carbon derived from distillation waste of citronella demonstrated their scavenging potential of toxic anionic dye congo red from water (Saha et al. 2020). The

Table 3 Production of smoke water from waste and its applications

Smoke water	Application	Soil	Crop	Utilization	Reference
Smoke water + KAR$_1$	SW: 1:500, 1000, 2000v/v, KAR10^{-7}, 10^{-8}, 10^{-9} M	Cd stress	*P. clandestinum*	Improve plant yield and phytoextraction potential	Okem et al. 2015
Cymbopogon jwarancusa	1:500 and 1:1000 v/v	Pb stress	*O. sativa*	Increase root length, fresh and dry weight, maintain antioxidant and metabolite	Akhtar et al. 2017
Smoke water	1:100 v/v	-	Prairie species	Seed germination and plant propagation	Krock et al. 2016
Smoke water	1/500 v/v	Mesic grassland	790 seeds in the soil seed bank	Increase seedling emergence and biomass production	Ghebrehiwot et al. 2012
Wheat straw smoke water + KAR$_1$	0.4 and 1% SW; 0.1 µM KAR$_1$	Boron stress	Wheat	Seed germination, reduce boron accumulation,	Küçükakyüz and Çatav 2021
Cymbopogon jwarancusa	2000 ppm, 1000 ppm, and 500 ppm	Soil with salt stress	Wheat	Regulate redox homeostasis genes and modulate stress regulatory gene expression	Hayat et al. 2021
Wheat straw	0.1%	Salinity stress	Wheat	Regulate expression of gene encoding transcription factor and antioxidant enzymes	Çatav et al. 2021
C. jwarancusa SW + Plant growth-promoting bacteria	1:500, 1:1000 v/v	Salinity stress	Rice	Increase germination percentage, and ion content, reduce metabolites and CAT, and POD activity	Khan et al. 2017
Fresh pine needle	1%, 2%, 10% and 100%	Biostimulator	Maize	Stimulate root growth and alter metabolite level, affect carbohydrate and energy-related metabolic pathways	Çatav et al. 2018
Smoke water + vermicompost leachate + seaweed extract	SW 1:1000 v/v, seaweed extract 0.6%, vermicompost leachate	Biostimulator	*Vigna unguiculata*	Increase seedling vigour index and plant biomass under heat stress, inhibit root stimulation in plant cuttings	Voko et al. 2022
Fallen leaves of *C.pinnatifida* and *M. denudata*	1:500, 1:1000 and 1:2000 v/v	Biostimulator	*S. miltiorrhiza*	Increase secondary metabolite content in hairy root culture, 1.2–3.3-fold improve in gene expression	Zhou et al. 2018
Rice straw	0.1, 0.2, 1, 2, 3, 4, 5, 6, 7 and 10%v/v	Biostimulator	Papaya	Increase nitrogen in root and shoot. Seed germination is 16.6% more than the control	Chumpookam et al. 2012
Themeda triandra	1:500 v/v	Biostimulator	*Allium cepa*	Promote both above and below-ground growth	Kulkarni et al. 2010
Cellulose, wood sawdust, olive residue, maize, alfalfa litter	1:100–1:1000 v/v	Pesticide activities	Lentil, lettuce, maize, tomato and wheat	Exhibit strong insecticidal and nematocidal properties	Bonanomi et al. 2021
Dry wheat straw	1/1000 v/v, 1/100 v/v, 1/10 v/v	Biostimulator	*A. cicer, D. glomerata, E. lanceolatus, L. angustus, P. smithii, P. juncea*	Stimulate seed germination and seedling emergence and increase standing crop	Abu et al. 2016

Table 4 Estimation of smoke water production and carbon price

Crop	Waste (t)	Smoke water production rate (L/t)	Smoke water (L)	Carbon content in smoke water (g/L)		C (kg)		Carbon price (Million USD)	
				Min	Max	Min	Max	Min	Max
Lemongrass	1,042,200	333	3129	50	61	156	191	0.008	0.011
Palmarosa	1,389,600	333	4172			209	255	0.01	0.016
Vetiver	93,798	333	281			14.1	17	0.001	0.001
Citronella	746,910	333	2242			112	137	0.006	0.008
P.graveolens	1,031,778	333	3098			155	189	0.008	0.012

Yield of smoke water Abdelhafez et al. 2021

Table 5 Overall economics and carbon dynamics in aromatic plant cultivation and waste valorization

	Minimum	Maximum
Production		
Net profit (Million USD)	22	629
Total C emission (t)	44	1824
Carbon emission price (Million USD)	0.002	0.104
BCseq in t	207,668	588,264
SCseq in t	107,694	221,950
Total Cseq cost (Million USD)	16.1	44.9
Hydrosol		
Total Cseq (t)	100	7403
C (Million USD)	0.01	0.42
Mulching		
Total Cseq (t)	147,826	2,629,123
Total Cseq cost (Million USD)	8	134
VM		
Production cost (Million USD)	1	13
Total Cseq (t)	2744	65,033
Total Cseq cost (Million USD)	0.2	3.3
Biochar		
Production cost (Million USD)	7	778
Selling cost (Million USD)	87	6149
Total Cseq (t)	935,635	33,558,840
C (Million USD)	48	1913
Fertilizer saving cost	0.08	6.27
Reduction in GHG emission (t CO_2/ha)	3349	105,610
Total Cseq cost (Million USD)	0.2	6
Smoke water		
Total Cseq (kg)	14.1	255
Total Cseq cost (Million USD)	0.001	0.016

leaf residues from the extraction of essential oils have been reported as good bio-sorbents for metal removal (Feisther et al. 2019). Biochar prepared from the distilled waste of lemongrass demonstrated the removal of 68–78% remazol brilliant blue R from the aqueous system (Singh et al. 2022). Biochar from aromatic grass spent showed maximum removal of Pb, Cd, and Cr 60 mg/g from the acidic mine waste (Khare et al. 2017). The use of biochar as an adsorbent could also provide economic gain. The removal of dye from the water costs 0.011 to 0.056 USD for 1 g of dye (Praveen et al. 2021). However, wastewater treatment costs by wood biochar were reported as 0.038 USD/m^3 (Fawzy et al. 2019). The presence of bioactive and nutrition-rich components such as polyphenolics, carotenoids as well as dietary fibres was reported in distilled waste (Ventura-Canseco et al. 2012). This waste also contained fibres like cellulose, hemicellulose, pectin, and silica, as well as crude protein (Yarin et al. 2022). Hence, distilled waste can be a suitable material for the preparation of animal feed. Many studies are available on the use of aromatic plants such as rosemary and lemongrass herbs for feed utilization and milk production in Pekin ducks and cows (Kholif et al. 2017; Suksombat et al. 2017; Linh et al. 2020). However, few studies are available on the utilization of residues of aromatic grasses. The lemongrass waste could be a substitute for elephant grass with high-forage feed (25%) without decreasing potential gas production, digestibility, and partial total VFA (Fidriyanto et al. 2021). Manurung et al. (2015) demonstrated that *Cymbopogon* residue could be a replacement for the conventional feed source (rice straw only) in ruminant diets. It was reported that ammonia and fermentation treatment on *C. nardus* waste could be used as an alternative to *P. purpureum*, which was used as forage for livestock (Elihasridas et al. 2021). This is an exciting area and needs to be explored more.

The biomass of different aromatic plants has a good amount of phenol and antioxidants (Parejo et al. 2002; Torras-Claveria et al. 2007). After the extraction of essential oil from plants, the phenolic content with diverse biological active components can be isolated, and the remaining biomass further utilized. However, distillation waste has comparatively lower antioxidant activity than the original plant material (Saha et al. 2021). Hence, the recovery of these antioxidants, economics, and carbon foot-printing needs to be explored further.

The Indian pulp industry is facing a problem of cellulosic fibre scarcity; hence the cellulose-rich aromatic grass spent can be used for the pulp industry. The pulp and paper-making potential of waste of *Citronella winterianus* demonstrated that distillation waste (kappa 18.72, yield 43.68%, viscosity 32.6 cp, and brightness 21.36%) exhibits nearly equal paper-making potential as original material (kappa number 20, 44–67% yield and 24% brightness) (Sharma et al. 2018, 2020). Likewise, *C. martini* produces a pulp yield of 43.7%, kappa number 20 at an active alkali dose of 14% Na_2O, and lemon grass produces a screened pulp yield of 41.4% of kappa number 12.5 (Kaur et al. 2011). The selling cost of cellulose pulp was reported as 1893–2440 USD/t (Alam and Christopher 2017).

Cellulose nano-fibers (CNF) obtained from native cellulose have become an essential area of research due to their unique properties, such as nontoxic, biocompatibility, and biodegradability. Cellulose nanofiber's unique properties make it suitable for numerous applications in the nanocomposite, food packaging, water purification, textile, pharmaceutical, and biomedical industries (Mishra et al. 2018a; Tibolla et al. 2019; Ma et al. 2011; Azeredo et al. 2017; Chauve and Bras 2014; Lee et al. 2014). Isolation of microcrystalline (yield 86%) and nanocrystalline cellulose (yield 77%) from the distilled waste of *C. winterianus* was prepared by acid hydrolysis and ultrasound-assisted TEMPO oxidation methods (Mishra et al. 2018a). The nano-crystalline cellulose obtained from distilled waste was used for the sustained release of synthetic drugs, bioactive molecules, and aroma compounds (Mishra et al. 2018b, 2021a, b, 2020, 2016; Mishra et al. 2021a, b; Kumari et al. 2019). Lemongrass-loaded NCC composite systems were shown to be inexpensive at less than $0.23/g (Mishra et al. 2018b).

8 Future prospects

For the sustainable restoration of degraded lands, technology should follow the concept of a circular economy which could be based on the reduction, recycling, and reusing of the available resources. The process should follow a regenerative model which aims for the maximum utilization of resources and to minimize the production of waste (Klemeš et al. 2020; Chiocchio et al. 2021). Among the available technologies, phytoremediation is an inexpensive and green technique for land restoration. The estimated costs for various methods used for soil treatments was 75–425 $/ton vitrification, 100–500$/ton landfilling, 100–500$/ton chemical treatment, 20–200$/ton electronic kinetics, and 5–40 $/ton phytoremediation (Glass 1999; Lasat 1999). Also, among these, electronic kinetics and phytoremediation processes require only short-term monitoring, while others require long-term monitoring, transportation, excavation, or recycling of contaminants. The cultivation of aromatic grasses on degraded land reduces the remediation cost by providing a net benefit of 22–629 million USD with sequestration of carbon (0.32–0.81 million tonnes and cost about 16–45 million USD) (Table 5). To make the process circular, the waste generated could be further used for the restoration of this land in the form of compost, vermicompost, and biochar. This further enhances the net productivity of the land and sequesters the carbon in the soil (Fig. 4). However, carbon locking in soil by different organic amendments prepared from DW i.e. biochar, vermicompost, and FYM could be depended upon the soil type and microbial availability. Among these, biochar can potentially store carbon for the centennial scale and has a positive effect on soil organic carbon sequestration (Ahsan et al. 2022; Rahman et al. 2020). However, vermicompost prepared from *Trianthema* will sequester soil carbon up to 35,590 kg ha^{-1} (128,836 kg ha^{-1} CO_2-e) over 100 years when applied as a soil conditioner (Naikwade 2019). Currently, the government of India is running a project called AROMA Mission for the cultivation of aromatic plants on degraded/marginal lands of India with a three-year target to cover the area (lemongrass 450 ha, palmarosa 400 ha, vetiver 200 ha, and citronella 50 ha).

9 Conclusions and environmental implications

This review indicates that the cultivation of aromatic plants on degraded land, along with the valorisation, can open new avenues for sustainability. The cultivation of the aromatic crop in degraded land not only increases the net productivity but also repairs the soil without any chemical intervention. Most of the studies showed the suitability of aromatic grasses in saline, acidic mine soils, dryland, and contaminated land; however, among these, few were large-scale field trials. Our estimation demonstrated that the cultivation of crops on degraded land could contribute to minimizing climate change. The high rate of biomass production in aromatic plants can sequester a huge amount of carbon by utilizing degraded lands. The valorisation of distilled waste for soil application (compost and biochar) and as plant growth promoters (smoke water) could further improve soil fertility and enhance productivity. In addition, the valorisation of generated distilled waste further sequesteres the carbon and participates in the reduction of GHG emissions from soils. Therefore, the process becomes circular and carbon negative with

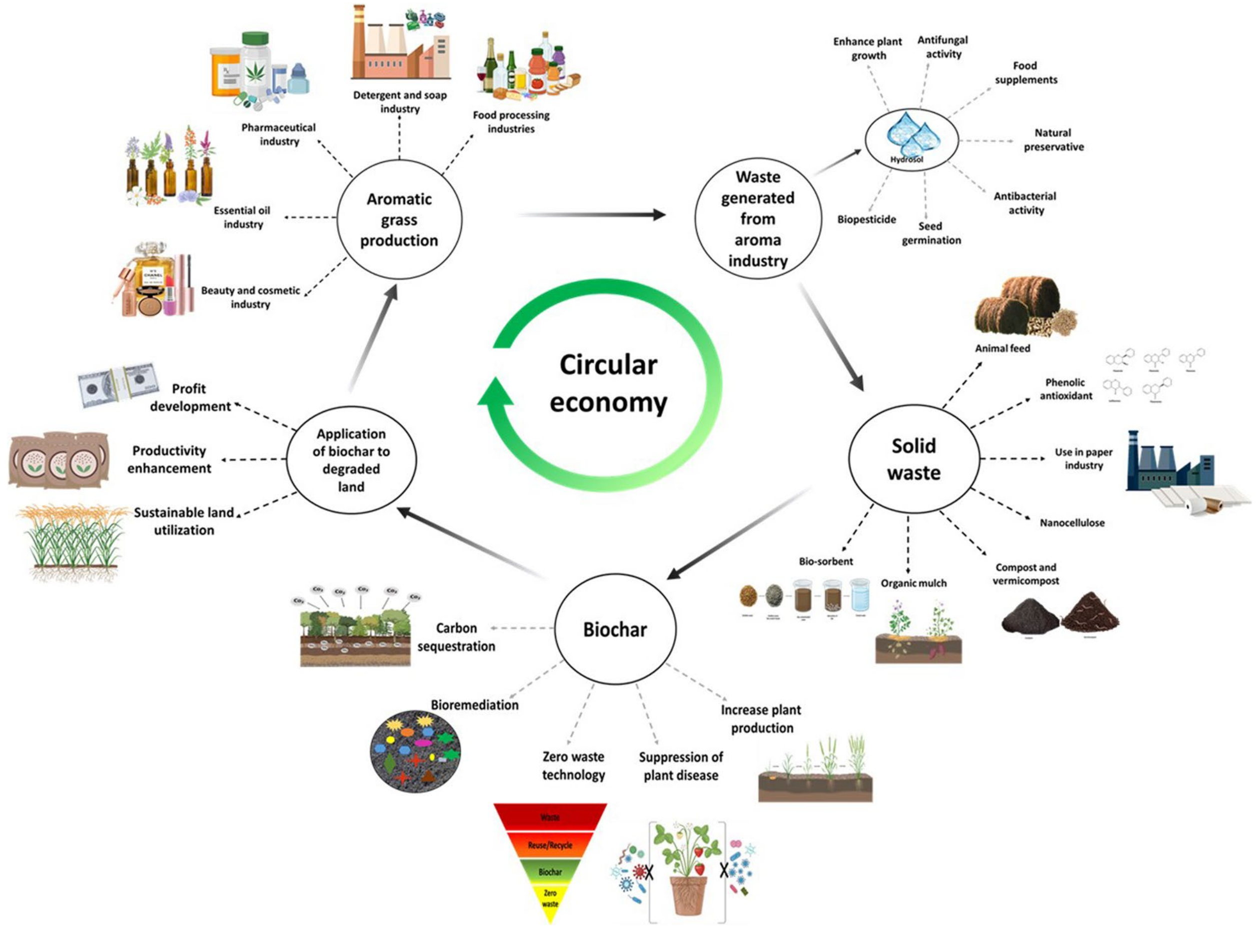

Fig. 4 Various aspects of cultivation of aromatic plants in degraded land towards the circular economy

zero waste. However, a comprehensive agro-climatic mapping of degraded land needs to be done to figure out the suitability of each aromatic plant for a particular climate and degraded land. The total carbon input and sequestration during the cultivation and processing of aromatic grasses need to be addressed before reaching any conclusions. No direct data was available on the carbon foot-printing of these aromatic plants during cultivation in degraded land. Further, the implementation of the cultivation of aromatic crops on a larger scale requires proper strategies along with life cycle assessment and carbon foot-printing of the process.

Abbreviations

SDG	Sustainable Development Goals
FAO	Food and Agriculture Organization of the United Nations
UN	United Nations
NRSC	National Remote Sensing Centre
Mha	*Million Hectares*
UNCCD	United Nations Convention to Combat Desertification
Mt	Metric Tones
VM	Vermicompost
FYM	Farm Yard Manure
DW	Distilled Waste
NPK	Nitrogen Phosphorous Potassium
t/ha	Tones/Hectare
SW	Smoke Water
v/v	Volume/Volume
w/w	Weight/Weight
ml	Millilitre
g	Gram
cv.	Cultivar
mg/g	Milligram/Gram
g/L	Gram/Litre
KAR	Karrikin
CNF	Cellulose Nano-Fibres
USD/kg	US Dollar/Kilogram
BCseq	Biomass Carbon Sequestration
SCseq	Soil Carbon Sequestration
USD/Km	US Dollar/Kilometre
USD/ha	US Dollar/Hectare
C/kg	Carbon/Kilogram
L/t	Litre/Tone
Kg/ha	Kilogram/Hectare
ha	Hectare
mg L^{-1}	Milligrams per Litre
t	Tone

CSP	Carbon Sequestration Potential
Cseq	Carbon Sequestration
FR	Fertilizer Replacement
S	Saving Cost
Eq	Equation
GHG	Green House Gases
TOC	Total Organic Carbon
spp.	Species
g/km	Gram/Kilometre
$/ton	Dollar per Ton

Supplementary Information

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Additional file 1: Supplementary 1. Total expenditure cost and net profit in cultivation of different aromatic grasses. **Supplementary 2.** Carbon sequestration potential of different aromatic grasses. **Supplementary 3.** Total carbon emissions during transportation and distillation of aromatic grasses. **Supplementary 4.** Total carbon content in hydrosol. **Supplementary 5.** Reported studies on valorization of distilled waste. **Supplementary 6.** Estimation of total hydrosol, mulch and Vermicompost production and its carbon price. **Supplementary 7.** Total carbon sequestration by mulching of distilled waste. **Supplementary 8.** Total carbon sequestration by vermicompost of distilled waste. **Supplementary 9.** Estimation of total biochar production and its selling price. **Supplementary 10.** Estimation of Cseq, fertilizer replacement and reduction in GHG emissions by produced biochar and Carbon price. **Supplementary 11.** Total carbon sequestration by biochar derived from distilled waste. **Supplementary 12.** Total GHG reduction by biochar derived from distilled waste. **Supplementary 13.** Total C sequestration by smoke water

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Authors' contributions

Deepika Yadav: investigation, formal analysis, and preparing the original draft, Anisha Yadav: formal analysis, Mayank Singh: formal analysis and editing; Puja Khare: conceptualization, replying reviewers and editing. The author(s) read and approved the final manuscript.

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Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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