Sustainable Lemongrass System Technology: An Integrated Approach for Industrial Effluent Treatment, Water Purification, and Soil Restoration

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Abstract
Water pollution from industrial effluents, heavy metal pollution, freshwater shortages and soil degradation are all a major environmental problem in the rapidly industrialized areas. Although effective, traditional physicochemical treatment technologies are expensive, energy-intensive, and result in secondary waste, so research on nature based solutions has been ongoing. A critical synthesis is presented of the findings of published literature for use of lemongrass (Cymbopogon citratus and C. flexuosus) as a potential technology for simultaneous treatment of industrial effluent, water purification and soil replenishment. The result of pot culture, lysimeter, and field scale studies shows that lemongrass can withstand a wide variety of soil and irrigation conditions, it is primarily a phytostabilizer for iron, manganese, copper, lead, nickel and chromium, and being grown for non-edible essential oil, does not present the risk of food-chain contamination as in other crop-based phytoremediation techniques. A comparative study of several different categories of industries (textiles, tannery, electroplating, mining and pulp and paper) shows that there is consistent performance up to a certain threshold, after which remediation capacity decreases. Based on this synthesis, the paper highlights an original integrated conceptual framework, Sustainable Lemongrass System Technology (SLSST), which integrates effluent treatment, phytoremediation, water reuse, extraction of essential oils, and biochar-based soil remediation, in a circular-economy-friendly system. It reveals actual consensus and conflicts it is found in the reviewed literature, especially those related to hyperaccumulator terminology, and the need for further research on some important topics, such as the lack of field validated integrated systems, techno-economic analysis and life cycle assessment. The technology is based on lemongrass and offers a promising alternative to the established treatment, with a potential good commercial co-production and sustainability, which requires separate field-scale testing and validation.

Keywords: Phytoremediation, Cymbopogon, Industrial effluent treatment, Heavy metal phytostabilization, constructed wetlands, Soil restoration, Circular economy

1. Introduction

In the last seven decades, industrial development has significantly boosted the amount of untreated or untreated effluent released into land and water, making wastewater pollution one of the most serious environmental problems of the 21st century (Ali et al., 2013). The effluents from textile dyeing units, tanneries, electroplating shops, pharmaceutical factories, metal processing plants and pulp and paper mills contain heavy metals, organic dyes and persistent chemicals that are not easily removed without effective treatment from conventional treatment plants (Mahar et al., 2016). Heavy metals (such as lead, cadmium, chromium, nickel, copper, zinc, arsenic and mercury) are toxic, non-biodegradable pollutants that remain in soil and water forever, get bioaccumulated in food chains and pose chronic health hazards even at trace levels (Yan et al., 2020).

Heavy metals have direct and well documented health impacts to humans in addition to their ecological persistence. Low-level chronic exposure to lead, cadmium, hexavalent chromium and arsenic are known or suspected to cause neurological, cardiovascular, and carcinogenic diseases, while chronic exposure to mercury is likely to cause neurological and cardiovascular diseases and cancer at low levels. These risks are disproportionately suffered by communities located near untreated or poorly treated industrial discharge points, often in low and middle income countries, where the ability to regulate and monitor industry and investments in treatment infrastructure fail to match industrial expansion, which is where most of the evidence presented in this paper for phytoremediation with lemongrass comes from.

Two parallel crises, increasing soil degradation and scarcity of freshwater are adding to the problem. Enormous amounts of wastewater generated globally goes untreated into the environment, a topic that has been repeatedly raised in the 2015 United Nations Sustainable Development Goal 6 agenda, while soil degradation due to further factors including heavy metal contamination, organic matters loss, salination and reduced microbial functionality has made vast areas of peri-urban and agricultural land in the industrial world unsuitable for conventional cultivation of food crops (Khan et al., 2023). This kind of pressure to find crops that will tolerate and actually help to improve the land to make it suitable for non-food commercialization is something that lemongrass is only right to respond to, as this review shows. Technically, these contaminants can be removed by the following conventional remediation methods: chemical precipitation, ion exchange, membrane filtration, electrocoagulation and soil excavation, but all are energy intensive, costly, create secondary waste streams, and are often impractical because they are used by economics systems where the majority of industrial discharge remains untreated (Qasaimeh et al., 2015). Such mismatch between contamination amount and the cost of remediation has led to continued scientific research into nature-based/plant-mediated remediation options.

One of the most promising, inexpensive, environmentally friendly, and sun-powered technologies now available is phytoremediation, which uses living plants and the associated rhizosphere microbiota to extract, stabilize, degrade or volatilize environmental pollutants (Salt et al., 1998; Pilon-Smits, 2005). Phytoremediation is performed at the same time as contaminant load reduction, soil structural improvement, sequestration of atmospheric carbon and the creation of biomass for harvest, making it very similar to a circular economy and nature-based-solution (Cunningham & Ow, 1996). Most of the research reported to date has focused on hyperaccumulator species that have a low biomass and a slow growth rate or on food and fodder crop plants that could pose a valid concern with the potential of heavy metals entering the human and animal food chain (Gupta et al., 2013).

Lemongrass (Cymbopogon citratus and Cymbopogon flexuosus), an essential-oil-producing, fast-growing perennial grass, which has been used for a long time in South and Southeast Asia, Africa and Latin America for a long time, provides a very attractive solution to this situation. Lemongrass is cultivated commercially to extract essential oil and hence, metal contamination in the vegetative parts of the plant does not pose a food safety risk, but its deep fibrous root system, high turnover of vegetative biomass, and adaptability to saline, alkaline and nutrient deficient soils make it well suited to the use of marginal and contaminated soils (Gautam et al., 2017; Khajanchi et al., 2013).

Increase in the amount of pot-culture, lysimeter and field investigations have revealed that the growth and yield of essential-oils, as well as the quality of the essential-oils obtained from lemongrass is largely unaffected within the permissible limits of contamination, however, its tolerance and partial stabilization capacity of different kinds of heavy metals such as lead, cadmium, chromium, nickel, copper, iron and manganese were observed on soils containing tannery sludge, mine tailings, fly ash and red-mud (Khilji & Sajid, 2020; Patra et al., 2018).

The intentional linkage of phytoremediation with the entire industrial-ecology cycle, however, remains relatively unexplored, with the effluent treated, the water purified and re-used, the soil regenerated and value-added added by essential-oil extraction and post-harvest biochar manufacturing/composting. Presently the literature focuses on different aspects of these phases separately from each other and some focus on phytoremediation efficiency, some on essential oil economics, and some on biomass valorization after harvesting, and no single treatment combines these three aspects specifically targeting the lemongrass crop. This review attempts to fill that void.

The purpose of this paper is threefold, first, it aims to critically summarise the relevant published peer-reviewed literature to determine the botanical suitability, the mechanisms of phytoremediation and the proven effectiveness of lemongrass in the remediation of industrial effluents; second, to compare and contrast the documented use of lemongrass in water purification and soil restoration with traditional and other nature-based technologies; and third, to formulate and discuss an original integrated conceptual framework, Sustainable Lemongrass System Technology, that brings together the treatment of effluents, water reuse, biomass recovery and soil restoration within a circular-economy model with the Sustainable Development Goals of the United Nations. The review is restricted to secondary and peer-reviewed publications, most of which have appeared in the past 10 years, and choice of certain foundational studies in cases of mechanistic understanding that was required.

The rest of this paper is organized as follows: Section 2 looks at the botanical characteristics of lemongrass and the particular qualities which enable its particular environmental uses. Section 3 explains the mechanism(s) of phytoremediation and the role of lemongrass in this mechanistic context. The issues of industrial effluent treatment are covered as a synthesis of the relevant sector-specific evidence with a comparative summary table in section 4. Water purification applications and restoration applications are considered in Sections 5 and 6, respectively. In Section 7 the central original contribution from the paper, the Sustainable Lemongrass System Technology, an integrated conceptual framework that links these different applications documented in the paper and makes them part of one circular-economy aligned system is developed. Section 8 reviews critically barriers, limitations and research gaps that need to be overcome for this framework to be translated from literature synthesis to field validation, and Section 9 ends.

2. Lemongrass: Botanical Profile and Environmental Potential

Lemongrass is part of the genus Cymbopogon, which is a group of about 180 tufted grasses (C4) characterized by aromatic leaf and flower parts. The two economically important species are Cymbopogon citratus (D.C.) Stapf (West Indian lemongrass), and Cymbopogon flexuosus (Nees ex Steud.). Both are grown extensively in India where they have a near monopoly of the world's essential-oil export trade; W. Watson, called East Indian or Cochin lemongrass.

Lemongrass is morphologically a dense bunch of many very stiff, blade-like leaves that droop towards the tips and give off a strong scent of citral upon crushing. Mature plants will reach a height of 60-120cm, sometimes up to 1.8m, and will survive for 4+ years with good management, which means that it is a low-maintenance, low-replanting perennial crop, not an annual.

Lemongrass is quite a simple plant to grow agronomically speaking. It can be cultivated at a wide soil pH range (about 5.0 to 8.4), and, as such, is appropriate for application in the phytoremediation of industrial sites that often have extreme or variable soil pH conditions, and is also tolerant of a wide temperature range (about 10 to 33°C, with optimal range from 25 to 30°C). It grows fairly well in full sun or partial shade, needs only moderate amounts of water if growing, and has an extensive rhizosphere microbial community, shallow root zone compared with woody plants, and is rhizomatous and fibrous, maximizing the surface area of contamination to which it is subject.

Studies of the root transcriptome have now started to address the molecular basis of this vigour and auxin response factor gene families were found to have tissue- and stage-specific expression patterns, directly correlated with biomass accumulation, a trait of practical importance, since biomass yield determines the amount of essential-oil produced and the total mass of pollutants handled per hectare from any phytoremediation application.

Lemongrass essential oil, the main commercial product of the plant, is extracted by steam distillation of the leaves and stalks and is composed mainly of two isomers, geranial and neral, which are nearly equal; citral normally accounts for 65–85 per cent of the total oil and is a mixture of these two isomers, which are known as geranial and neral, respectively. This chemical profile is well documented to give antibacterial, antifungal, antiviral, antioxidant, and anticancer bioactivity as evidenced by its use in the commercial markets in food flavouring, cosmetics, aromatherapy, and pharmaceuticals and more recently the application to biocorrosion inhibition in petroleum pipelines against the reduction of sulfates. The fact that India has an effective monopoly on lemongrass oil production and export suggests that decades of the established agronomic infrastructure, extraction capacity, and international market access could enable lemongrass oil to be produced and exported as a remediation-use crop without the need to establish a new supply chain.

Three attributes make lemongrass unique from an environmental engineering perspective as one of the species which is being considered as a phytoremediation species. First, and most fundamentally, non-edible: Due to the fact that plants are grown for their oil content rather than for food or for fodder, the addition of metal collected in the plants by plant cultivation is not a direct "food chain" contamination pathway, overcoming one of the main ethical and regulatory concerns of agricultural crops used for metal phytoremediation (Gupta et al., 2013). Second, the empirical evidence suggests that essential oils yield and quality are fairly resilient against moderate levels of heavy metal and wasted water use: Experiments with the amendment of red-mud and sewage sludge in lemongrass have reported that high levels of heavy metals and sewage sludge do not significantly affect essential oil composition or yield (Gautam et al., 2017). Third, lemongrass has a metal tolerance that is adequate for its survival in moderately contaminated industrial areas, while also having a relatively high biomass turnover rate and a—more or less—fast growth rate that are rarely observed in classical hyperaccumulator species (exhibiting low growth and/or biomass per unit area and often being site endemic, Baker & Brooks, 1989; Brooks, 1998).

While this should be considered cautiously, it should not be viewed as a blanket endorsement of the properties. Although in the phytological sense Lemongrass is not considered a hyperaccumulator, the most dominant behaviour that was observed in the literature on pot culture reported here is the phytostabilization, with the metals being bound preferentially in the root tissues with comparatively low translocation to the shoot tissues (Gautam et al., 2017; Patra et al., 2018). This is an important point to note as a practical advantage of phytostabilization is that it decreases the pollutant mass's mobility and bioavailability on-site, without needing to physically remove and transport it away from the site, which the paper also addresses in Section 3. Lemongrass can therefore be described not as a hyperaccumulator of metals, but a phytostabilizer that produces good biomass with commercially marketable, low-risk aerial biomass – in other words, a moderate-tolerance phytostabilizer with low risk aerial biomass for use in an integrated remediation system.

Generally similar, but not congruent, remediation behaviour is suggested, based on comparative evidence from the two major species. C. citratus is more widely tested for metal tolerance under different amendment (red-mud, fly-ash, and sewage-sludge) conditions; it has been observed to phytostabilize the metals of Fe, Mn, Cu, Pb and Ni and has shown MTSI values >100 percent in medium level of metal contamination (Gautam et al., 2017). However, the species used in the tannery-sludge and the hexavalent-chromium dose-response trials has been C. flexuosus, in which growth parameters, such as fresh and dry biomass, number of tillers and chlorophyll contents start to decline significantly when the amendment rate exceeds about 10 to 15 percent, representing a greater phytotoxicity threshold above which remediation effectiveness and the economics of essential oils start to diminish (Khilji & Sajid, 2020; Patra et al., 2018). Overall, it is concluded that the decision to implement a species or cultivar in any site-specific lemongrass remediation programme should be based on the species rather than on the genus.

3. Phytoremediation Mechanisms

Phytoremediation generally applies the action of living plants and the microorganisms in the rhizosphere to remove, immobilize or degrade contaminants from soil, water, sediments and air (Salt et al., 1998). Elucidated in the 1990s, the field has coalesced around 5-6 major mechanistic pathways – including phytoextraction, phytostabilization, rhizofiltration, phytodegradation, phytovolatilization and rhizoremediation – that target different kinds of contaminants and matrices, and rely on distinct plant physiological and microbial processes (Meagher, 2000; Muthusaravanan et al., 2018; Sharma et al., 2023).

The term phytoextraction (also known as phytoaccumulation) describes the incorporation of contaminants, primarily metals, into the biomass of plants by the root system and the subsequent transfer in the plants to parts that can be removed from the contaminated area by harvesting the biomass (Kumar et al., 1995; Chaney et al., 1997). This is the most direct way to obtain the greatest reduction in total contaminant mass at a site, but is limited by the extent of root system penetration (typically 30 to 90 centimetres for herbaceous species); the metal-specific metal translocation efficiency of the selected plant; and a trade-off between high tissue concentration plants (hyperaccumulator species) and high total metal mass being removed per hectare (Mahar et al., 2016; McGrath & Zhao, 2003).

Phytostabilization is, however, not designed to remove contaminants from the site entirely, rather aims to immobilize the contaminants within the root zone so that they are not available for leaching, bioaccumulation or wind and water erosion (Yan et al., 2020; Bolan et al., 2011). The pollutant does not need to be removed, so phytostabilization does not involve the disposal problem of contaminated biomass but is far simpler and less expensive to be implemented at large scales and verified periodically whether the pollutant is being immobilized.

Rhizofiltration is similar to phytoextraction in that the root systems of plants, in this case typically already grown in a nutrient solution, are exposed to the contaminated water, and roots absorb and absorb metal ions in the water, which are later harvested along with the rest of the root biomass (Raskin et al., 1997). The purification of water from this mechanism is different from the intended phytostabilization of contaminants bound to the soil, and is described in Section 5.

Phytodegradation is the biochemical degradation of organic contaminants such as some pesticides, hydrocarbons and explosives in the plant tissues through internal metabolic pathways (Susarla et al., 2002), and phytovolatilization involves the uptake of some of the volatile organic contaminants or rapidly volatilized contaminants like selenium and certain forms of mercury and their subsequent release, either in the modified or unmodified form, through the stomata in the leaves into the atmosphere (Sharma et al., 2023). The latter is not directly relevant to the context of industrial effluents, which tend to involve high levels of many metals, but phytovolatilization is of secondary importance and has a known problem: the remediated metal becomes airborne instead of being removed from the soil or water, a factor that often poses a problem in regulation (Yan et al., 2020).

Finally, rhizoremediation relies on the synergistic rhizosphere/plant relationship: root exudates (sugars, organic acids, amino acids) provide the stimulation and support necessary for population of bacteria and fungi in the rhizosphere that degrade pollutants, and much of the actual pollutant degradation occurs by these microorganisms. The dense fibrous network of secondary roots of grasses, in particular the Cymbopogon species, provides a very large area of roots in relation to soil bulk volume and thus a large and diverse rhizosphere microbiome.

Heavy-metal uptake and detoxification in plants occurs in a concerted mechanism, including root-surface adsorption and ion-channel-mediated uptake, chelation by intracellular ligands like phytochelatins and metallothioneins, and sequestration in vacuole, which sequesters the metal away from metabolically sensitive cytoplasmic compartments (Sharma et al., 2023). Efficiency of this sequence and therefore the general efficiency of phytoextraction or phytostabilization depends on a complex set of interacting factors such as plant species and genotype, the speciation and bioavailability of the metals in the growth medium, soil pH and redox potential, the presence or absence of plant growth promoting and metal resistant rhizobacteria, and the use of chelating agents and soil amendments that can release otherwise recalcitrant fractions of metals (Yan et al., 2020; Ma et al., 2011).

Specific evidence for lemongrass places the species firmly in the category of situating it in the category of "phyto-stabilization" as opposed to phytoextraction. The empirical trend is observed as the main mass of the absorbed metal gets deposited in root tissue, and comparatively lesser amount translocated to the aerial parts, across both the independent pot-culture and in situ trials ranging from red-mud amended soil, to mine tailings, tannery sludge and hexavalent-chromium dose-response experiment, and the corresponding elevated bioconcentration factor (BCF) values compared to translocation factor (TF) (Gautam et al., 2017; Patra et al., 2018). This is scientifically consistent with the plant root tolerance strategy, which is by sequestering the metals within the vacuole of root cells; this is also consistent with the low sensitivity and relatively high essential-oil concentration and yield, which are synthesized in glandular tissue of leaves and stems (Gautam et al., 2017). The endogenous phytostabilization capability of lemongrass has been demonstrated to be improved under Cr and mixed metals stress by various enhancement strategies documented in literature, co-inoculation with plant-growth-promoting rhizobacteria like Bacillus cereus and application of metal chelators such as EDTA, DTPA, citric acid, salicylic acid that can be enhanced without the genetic modification of the plant per se (Patra et al., 2018).

Terminology is one area where the literature has not been fully reconciled, as some studies report on hydroponics or high tolerance conditions where the plants qualify as hyperaccumulator and others report translocation factors below the conventional threshold for hyperaccumulator in dose-response trials with soil-based plant growth, but present a clear phytostabilization trend. This review follows the more conservative classification definition of phytostabilizers (cited by M.D. Radelka and D. Lavine) but notes that under certain matrix conditions (aqueous / hydroponic exposure), a more like rhizofiltration, higher bioconcentration behaviour has been reported. This caution with terminology is important for the integrated system proposed in Section 7 because it helps to frame realistic expectations for the extent to which contaminant mass can be physically removed from a site, as opposed to immobilized.

4. Industrial Effluent Treatment Using Lemongrass

There is a significant variation in composition among industrial wastewater streams that directly affects the ability of a lemongrass-based system to function, and possibly how well.

Textile industry. The dyestuff and textile finishing industry produces high volume, complex, chromatic effluents and wastewater that contain azo and other synthetic dyes that are hard to bio-degrade and are associated with formation of carcinogenic intermediate breakdown products of the dye. Recent use of the phytotechnological approaches to textile effluent has included the use of constructed wetlands and the synergism between plants and bacteria, and, of particular relevance for lemongrass, the use of postharvest value-added biomass as an activated carbon: activated carbon produced from lemongrass-leaf biomass has been used to remove approximately 65% of methylene-blue dye from water. Indirect, but supportive evidence of the underlying phytoremediation mechanism has been obtained by conducting complementary in situ tests with other grasses and ornamentals that are grown in ridges, where colour-value reductions of 46-73 percent occurred in 30 days with measurable reductions of heavy metals in both planted and unplanted soil.

Tanneries. Leather-processing effluent has some of the most highly polluted industrial waste streams with extremely low pH and higher than normal biological and chemical oxygen demand, high total dissolved solids and chromium concentrations of up to 1,500 to 3,000 parts per million (ppm) in chrome tanning practice. In this context, there is direct experimental evidence for lemongrass: C. flexuosus grown on soil amended with 5, 10 and 15 percent tannery sludge showed clear, dose-dependent phytotoxicity, with fresh weight, dry weight, root number, leaf number, tiller number and shoot length all measurably reduced by up to roughly 37.5 percent at the highest sludge concentration, while the plant still survived and metal accumulation was recorded in the root tissue at all treatment levels (Khilji & Sajid, 2020). This finding is significant as it simultaneously showcases the feasibility, survival of the plant as a phytostabilizer and provides practical limits on the level of contamination at which lemongrass can be considered agronomic and economically viable as an alternative, which is often overlooked in more positive secondary research.

Electroplating and metal processing companies. The predominant metals in electroplating effluents are the direct result of the electroplating chemistry: dissolved cadmium, chromium, copper, nickel, arsenic, lead and zinc, and the effluents from this process are considered to be one of the most metal-laden of all industrial effluents. The studies performed on mine-tailings and red-mud contamination provide a reasonable proxy as they are contaminated similarly by a suite of metals, including Fe, Mn, Cu, Cd, Ni, Zn and hexavalent chromium and also showed an increased biomass and metal content in the co-cultivated samples compared to controls where no rhizobacteria were added, functioning primarily as a root-zone phytostabilizer on the test metal suite. This transferability is possible but has not yet been demonstrated in practice with wastewater from electroplating in particular, and is therefore a target for research.

The mining and mineral-processing industries. The most extreme and persistent cases of heavy metal contamination often occur at mine tailings and overburden dumps where concentrations of hexavalent chromium, iron, manganese and other metals are present at levels which are toxic to most typical vegetation. C. flexuosus revealed a clear dose-response relationship, with stimulation of plant growth at low chromium levels (c. $10 mgkg^{-1}$), and inhibition of plant growth and decreases in chlorophyll content under the high chromium levels (c. $100 mgkg^{-1}$ Cr^{6+}); and application of chelating agents partially recovered plant growth under the toxic levels (Patra et al., 2018). These results confirm the value of using lemongrass for the revegetation and phytostabilization of moderately polluted overburden material, as most of the literature on phytoremediation recognizes hexavalent chromium as being acutely phytotoxic for most higher plants at the contamination level above approximately 100 micromolar per kilogram dry weight.

Pharmaceutical/chemical industries. Wastewater from pharmaceuticals does not contain heavy metals in its composition, instead it usually contains residues of antibiotics, non-steroidal anti-inflammatory drugs and other bioactive organics, but not heavy metals themselves. Although to date, there is no direct evidence of the ability of these lignocellulosic-based biosorbents to remove pharmaceutical micropollutants, the fact that they have already been demonstrated to remove pharmaceutical contaminants of agro-industrial residues such as bagasse, husks, or straws (with varying efficiency) renders their use directly relevant to the integrated framework proposed hereafter and uses biochar as the relevant sorbent: post-harvest biomass of lemongrass is compositionally similar to the other agro-industrial residues shown to be effective as pharmaceutical-residue sorbents, with the exception of straws.

Food processing and pulp and paper manufacturing. These include those producing high organic load comparatively low toxicity effluents compared to tanneries and electroplating units, but have measurable heavy metal loads in the effluent. The rates of removal of these metals for the planted constructed wetlands were found to be greater than the unplanted control, with a 20 to 40 percent increase due to plants and the processes associated with the rhizosphere (Arivoli et al., 2015). This amount of vegetation removal is directly relevant to the potential maximum performance of a constructed system treating effluent of similar characteristics with a lemongrass species not tested here.

The results of the above discussed findings on each major contaminant covered in the literature are summarized in a table (Table 1) that combines the removal/stabilization mechanism, source industry and supporting evidence for each contaminant.

Table 1: Industrial Pollutants Removed or Stabilized by Lemongrass

Pollutant	Source Industry	Removal / Stabilization Mechanism	Key Findings	Supporting Reference
Iron (Fe)	Mining, red mud, tannery	Phytostabilization (root retention)	Tolerance index above 100%; metal concentrated in root tissue under red-mud and biowaste-amended soil	Gautam et al. (2017)
Manganese (Mn)	Mining, red mud	Phytostabilization	Root-concentrated accumulation under sewage-sludge and red-mud co-amendment	Gautam et al. (2017)

Copper (Cu)	Red mud, pulp and paper	Phytostabilization; constructed-wetland uptake	Root stabilization in lemongrass trials; approximately 80% removal in planted pulp-and-paper constructed wetlands	Gautam et al. (2017); Arivoli et al. (2015)
Lead (Pb)	Red mud, general industrial, mixed-metal sites	Phytostabilization	Efficient root-level stabilization reported under red-mud and cow-dung-amended soil	Gautam et al. (2017)
Nickel (Ni)	Red mud, pulp and paper, electroplating	Phytostabilization; constructed-wetland uptake	Root stabilization in lemongrass; approximately 71% removal in planted pulp-and-paper wetlands	Gautam et al. (2017); Arivoli et al. (2015)
Chromium (Cr, incl. Cr6+)	Tannery, electroplating, chromite mining	Phytostabilization; threshold-limited	Growth stimulated at 10 mg/kg, inhibited above roughly 100 mg/kg Cr6+; up to 37.5% biomass reduction at 15% tannery sludge; chelators enhance uptake	Khilji & Sajid (2020); Patra et al. (2018)
Cadmium (Cd)	Tannery, mining, electroplating	Phytostabilization	Root accumulation documented under multi-metal contamination; constructed-wetland benchmark removal up to 92% in non-Cymbopogon systems	Khan et al. (2009)
Zinc (Zn)	Pulp and paper, general industrial	Phytostabilization; constructed-wetland uptake	Approximately 70% removal reported in planted pulp-and-paper constructed wetlands	Arivoli et al. (2015)

This sector-by-sector synthesis highlights several cross-cutting comparative observations. Lemongrass' efficacy as a phytostabilizer for iron, manganese, copper, lead and nickel was consistently the most effective, whereas its efficacy as a phytostabilizer for hexavalent chromium and cadmium was more variable and its threshold appeared more sharply, reflecting different chemical mobilities and phytotoxicities of these elements (Gautam et al., 2017; Patra et al., 2018). Second, direct dedicated trials are still limited to amendment scenarios (soil, red mud, fly ash, tannery sludge, and mine tailings), and trials using wastewater and constructed-wetland-format with lemongrass, compared to traditional wetland macrophytes, are comparatively under-represented, so much of the sector-specific extrapolation offered above, specifically for electroplating and pulp-and-paper effluent, is based on reasonable but not yet directly validated analogy. Third and most encouragingly for the real-world application, the literature suggests that the wastewater-irrigation application can use primary treated municipal and/or industrial wastewater without causing a build-up of heavy metals in essential oils over permissible limit and may enhance the soil's fertility status through application (Khajanchi et al., 2013), which is an advantage not often provided by conventional wastewater treatment facilities.

This is complemented by the summary of the main published studies reviewed in this paper, in Table 2, which maps each study onto its study type, contaminated medium, and main results, and makes explicit the geographic concentration of the evidence base (South Asia) and the methodological concentration (pot-culture and lysimeter trials).

Table 2: Major Published Studies on Lemongrass Phytoremediation

Author(s)	Year	Country	Study Type	Contaminated Medium	Main Findings
Gautam, Pandey, & Agrawal	2017	India	Pot-culture	Red mud and biowaste-amended soil	Phytostabilizer of Fe, Mn, Cu; efficient Pb and Ni stabilization in roots; essential-oil yield largely unaffected at moderate contamination
Khilji & Sajid	2020	Pakistan	Pot-culture	Tannery sludge-amended soil	Dose-dependent growth inhibition, up to 37.5% at 15% sludge; plant survived and accumulated metals across all treatments
Patra, Pradhan, & Patra	2018	India	In situ pot trial	Chromium (Cr6+)-spiked mining overburden soil	Growth stimulated at 10 mg/kg Cr6+, inhibited at 100 mg/kg; chelators enhanced uptake and growth recovery

Khajanchi et al.	2013	India	Lysimeter trial	Wastewater-groundwater irrigation	Herbage and essential-oil yield increased under wastewater irrigation; oil heavy-metal content within permissible limits
Pandey & Singh	2010	India	Experimental review	Fly-ash-amended soil	Reviewed impact of fly-ash incorporation on soil systems; supports revegetation potential of tolerant grasses
Khan, Ahmad, Shah, Rehman, & Khaliq	2009	Pakistan	Field constructed wetland	Industrial estate wastewater (non-Cymbopogon macrophytes)	40.9-91.9% removal efficiency across Pb, Cd, Fe, Ni, Cr, Cu; established benchmark for constructed-wetland performance
Arivoli, Mohanraj, & Seenivasan	2015	India	Field constructed wetland	Pulp-and-paper industry effluent	Planted wetland removed 60-80% of Fe, Cu, Mn, Zn, Ni, Cd; substantially outperformed unplanted control

5. Water Purification Applications

In addition to the soil-based phytoremediation, it is relevant to water purification because of the ability of lemongrass and its constructed-system analogues to uptake the contaminants via rhizofiltration (Section 3) and because of its use as a precursor biosorbent after harvest.

Although many species of macrophytes have been used in most of the constructed-wetland research studies performed to date, the majority have focused on species other than Cymbopogon (Vymazal, 2014; Kadlec & Wallace, 2009), constructed wetlands are the most mature and best quantified water-treatment-based technology broadly applicable to the lemongrass system concept. Heavy-metal removal efficiencies reported from constructed wetlands are great and remarkably comparable in magnitude despite the wide variety in the composition of waste discharged to them, in terms of heavy-metal species, as well as in design, flow specifications, and wetland construction procedures; for instance, in Qasaimeh et al. (2015), the reported combined metal removal efficiencies for copper, lead, and zinc are between 82 and 92 percent; in a continuous free-surface-flow wetland treating wastewater from an industrial estate in Pakistan, reported metal removal efficiencies are 48.3 percent for copper, 50 percent for lead, 74.1 percent for iron, 91.9 percent for cadmium, 89 percent for chromium, and 40.9 percent for nickel (Khan et al., 2009). This result was comparable with the vertical flow wetland treating pulp and paper effluent which showed the removal efficiency of 74-80 percent for iron and copper, and again planted systems performed 20-40 percent higher than the controls, similar to the rest of the literature on wetland macrophytes for aquatics heavy metal removal (Rai, 2008; Dhir, 2013).

Mechanistically there are several pathways for metal removal in a constructed wetland which operate concurrently: direct plant uptake, the rhizofiltration and phytoextraction pathways mentioned above, adsorption onto root surfaces and wetland's substrate or sediment, microbially mediated precipitation and sulfide formation under the variable redox conditions within the constructed wetland, and physical sedimentation of particulate-bound metal (Qasaimeh et al., 2015). This mechanistic diversity is one of the main advantages of the constructed-wetland format when compared with a single-mechanism treatment technology, since the removal pathway can still operate even if one pathway, such as metabolic activity for plants during the winter months, is being sub-optimal or even ineffective.

In comparison to the conventional physicochemical treatment, chemical precipitation, ion-exchange resins, reverse osmosis and electrocoagulation, nature-based treatment systems, such as lemongrass-integrated constructed wetlands, have several documented comparative advantages: a significant reduction in capital and operating costs, minimal or no consumption of chemical reagents, no continuous energy input for aeration or pumping in gravity-fed systems, and the production of an output which is a co-generation – harvestable, saleable biomass output instead of a hazardous sludge that must be disposed of at an additional cost. Real constraints of constructed wetlands include that they need significantly more space per volume of treated wastewater than the more compact physicochemical treatment plants, they are less tolerant of seasonality and climatic fluctuations, and, as in soil-based phytoremediation, the high concentrations of some metals in the wastewater can reduce plant growth and hence treatment efficiency. This indicates that such systems are more likely to be used as a secondary or tertiary polishing system after initial physicochemical treatment of the most concentrated effluent streams than as the primary treatment for undiluted industrial effluents.

The evidence base for water-purification use of lemongrass is based on two lines of evidence. This direct evidence is of the type known as "rhizofiltration," and hydroponic experiments in which lemongrass roots were exposed to effluent contaminated with heavy metals have shown significant decreases in heavy metal uptake in the effluent as well as bioconcentration factors greater than one for several heavy metals tested, indicative of active root uptake from the liquid phase. Another indirect, but perhaps more commercially important, is the fact that dedicated wastewater-irrigation trials have proven that lemongrass can be successfully grown under controlled irrigation-to-evaporation ratios (IER) while pumping primary-treated municipal or industrial wastewater, without the essential oils containing biologically toxic levels of heavy metals after the crop has acted as a polishing stage during its percolation through the root zone and soil profile (Khajanchi et al., 2013).

Lemongrass' water-purification significance continues after the growing phase. The spent lemongrass biomass after essential-oil extraction is used to make activated carbon, which is demonstrated to adsorb about 65% of the methylene-blue dye from aqueous solutions, and separately, to make biochar that is found to have nutrient and water-retention properties, and is applied to soils. The dual use aspect for in-field treatment, obtained with the biomass of plant species, and for post-trapping treatment downstream, with the residue, is a characteristic feature of the lemongrass system when compared with standard constructed-wetland macrophytes whose biomass is generally left in situ or lost, is exploited further as a basic structural component of the integrated system introduced in Section 7.

Treating the water to make it potable is the natural culmination of this filtration process if reused. Pollutant reductions allow the treated effluent to be recycled for additional irrigation of crops, including more lemongrass production, for industrial processes (e.g. for cooling and washing), and for the controlled recharge of ground water, completing a local water loop, especially valuable in water stressed industrial regions of South Asia where the majority of the primary evidence base comes from for the use of lemongrass-based systems to enhance water quality for non-potable uses (World Health Organization, 2011).

6. Soil Restoration

The problem of restoring heavy-metal contaminated, fly-ash or red-mud contaminated industrial land is different from that of water treatment, in that the latter aims to remove a mobile load of pollutants and the former aims to restore a self-sustaining, ecologically functional soil system on a site where the contamination is in most realistic situations present at some residual level for the foreseeable future.

As demonstrated in Section 3, phytostabilization is the mechanism that lemongrass most reliably and consistently engages with, and it is an ideal mechanism for this objective. Lemongrass sequesters absorbed metals in root tissue, changes rhizosphere micro-chemical environment, changes micro-pH and micro-redox condition, and releases organic acids and other ligands to bind metal ions, without physically removing the contaminant from the soil, which decreases the leachability and bioavailability of soil-bound contaminants (Bolan et al., 2011; Yan et al., 2020). However, this is a materially important difference from phytoextraction-based restoration approaches because the aim is in-place immobilization, instead of extraction, which results in a lesser problem of disposing of the metal-enriched harvested-vegetation, the vegetation cover itself provides immediate tangible benefits such as suppression of wind- and water-driven erosion, reduction of fugitive dust generation, and prevention of direct human and animal contact with exposed contaminated substrate (Yan et al., 2020).

In addition to metal stabilization, soil-forming processes that are generally documented in the literature under the umbrella of phytostabilization and field-crop remediation, measurably shift as vegetation cover develops, from a bare and geochemically inhospitable substrate to a functional pedogenic system (Vamerali et al., 2010; Kabata-Pendias, 2000): physicochemical parameters such as pH buffering, organic-carbon accumulation, and soil particle-size distribution shift measurably from a bare and geochemically hostile substrate to a functional pedogenic system as vegetation cover develops. Application of organic amendments like compost, farmyard manure, biochar and other industrial by-products like sewage sludge at controlled rates have consistently proven to improve this process when co-applied with lemongrass, and here, the iron, manganese and copper tolerance indices for the former are well above 100 percent (sewage-sludge-and-red-mud co-amendment trials record TIs > 100 percent for iron, manganese and copper, while fly-ash-amended trials demonstrate that it can be established as a revegetation species on combustion-residue deposits that would otherwise be sterile; Gautam et al., 2017; Pandey & Singh, 2010).

An intriguing discovery for soil-restoration practice is that the biochar production from lemongrass, a step within an integrated system suggested in Section 7, is also a soil amendment. Biochar derived from slow pyrolysis of the spent lemongrass distillation residue when mixed with farmyard manure and supplemented with low-grade rock phosphate and waste mica in the form of biochar-mineral complex proved to be able to appreciably enhance the yield and bioactive-compound content of an subsequently grown medicinal crop when cultivated on deeply weathered, acidic soil, respectively than pristine biochar or farmyard manure. This is important to note because it shows that the leftover material from a first cycle of growth of lemongrass can be used as a soil improvement input in a second cycle of growth – either of lemongrass or a different crop – rather than as a terminal waste stream to be disposed of separately.

Another often overlooked aspect of soil restoration is microbial growth and activity. Plant growth promoting rhizobacteria and metal resistant rhizobacteria like Bacillus cereus, when co-inoculated with lemongrass, was found to increase plant biomass and metal uptake by plants compared with control, and also vegetation cover helped in recolonization of degraded soil by microbial community suppressed by the initial contamination event (Ma et al., 2011). The soil rhizosphere-microbiome effect is not just the addition of the stabilizing function of the metals normally highlighted in phytoremediation studies, but also encompasses the protective role of the soil in regulating nutrient cycling, organic-matter decomposition, and plant available N and P that are also recognized benefits of soil.

Documented benefits notwithstanding, the literature of soil restoration also points to significant limitations common with phytostabilization as a strategy, and relating to the use of lemongrass. Vegetation cover is left in place and does not need to be removed, so phytostabilization-based restoration will involve maintenance of this vegetation cover and the need to check from time to time to ensure that the contaminants are still being immobilized by the vegetation cover, and are not being remobilized as a result of disease, extreme environmental conditions, land-use mismanagement or premature conversion to land use (Bolan et al., 2011). Likewise, one of the limitations of effective stabilization is the depth at which the plants can enter the soil (the root penetration depth), and the effectiveness of lemongrass-based restoration is limited to surface contamination and near surface soil contamination (typically the upper 30-60 cm of soil), which is typically the extent of the subsurface plumes that require complementary engineering work. While these limitations do not reduce the demonstrated utility of lemongrass as an inexpensive, high-yield revegetation/soil stabilization option for moderately contaminated surface soils, they do require that any soil-restoration projections be put in context of a longer-term (maintenance dependent) immobilization/ecological rehabilitation, not decontamination, goal.

7. Sustainable Lemongrass System Technology:An integrated approach

Up to now, the botanical suitability of lemongrass, its phytoremediation mechanism, and its verified application area (industrial effluent treatment, water purification and soil restoration) have been discussed. What the current literature has forgotten to integrate and what is in this section centralized as an original contribution to this review and is the central achievement of physical and economic integration, is to connect these three aspects together and produce a single physically and economically-integrated system, Sustainable Lemongrass System Technology.

The ten stages of the proposed system architecture are shown in Figure 1. Untreated industrial effluents from any of the above mentioned sectors in section 4 containing pollutants above 10-15 percent contamination equivalent loading have been found to decrease the growth performance of the lemongrass and thereby reduce the system efficiency, thus preliminary treatment, screening and sedimentation is being employed with or without some degree of physicochemical pretreatment depending on the concentration of contaminants present in the industrial effluents (Khilji & Sajid, 2020; Patra et al., 2018). Drawing on the evidence synthesized in Sections 4 and 5 for wastewater-irrigation and constructed-wetlands respectively, the pretreated effluent then feeds into the phytoremediation system using lemongrass as an entity in itself, whether as a soil-bed/constructed-wetland hybrid for use with streams having a high metal concentration or as a controlled wastewater-irrigation regime in streams with less metal and a higher organic and nutrient load. In this phase of water purification, the combination of phytoextraction, phytostabilization and rhizofiltration accompanied by the activity of rhizosphere microorganisms is taking place, with the purified water reaching a threshold quality appropriate for reuse in irrigation, industrial process water, or controlled discharge, thereby closing the water loop and directly addressing the water-scarcity dimension of the sustainability rationale developed in Section 1.

The unique aspect of the system compared to the constructed wetlands or generic phytoremediation is the use of the retrieved biomass as part of the second productive phase. Since lemongrass is a perennial species that can be mowed multiple times, biomass harvesting is implemented as a rotation; by contrast, in phytoextraction-based systems, plants are completely removed from the root zone after harvesting. The harvested biomass is then subjected to the essential-oil extraction via conventional steam distillation, which is a marketable product, whose heavy metal content, as per the literature surveyed above in sections 1 and 2 on wastewater-irrigation and red-mud-amendment, stays within permission limits under moderate contamination-perdicted conditions (Gautam et. al 2017; Khajanchi et. al 2013), which is critical safety property, distinguishing this framework from food-crop-based phytoremediation schemes and directly addressing the food-chain-contamination objection in sections 1 and 2 above.

The spent, post-distillation biomass residue, instead of simply being discarded, as is done in most traditional essential oil processes, starts a third recovery cycle as feedstock for biochar production, composting or as a raw material for controlled thermal processing for energy recovery via pyrolysis, when residual metal levels are sufficiently high. Pyrolysis of the lemongrass distillation residue has been reported; the products were a phenolic-rich bio-oil which could be used as an energy source or as a chemical feedstock and a biochar which has been shown to possess soil-amendment properties when used in combination with organic and mineral co-amendments. This biochar, followed by the composted biomass-fractions, completes the circular process for soil improvement by applying the biomass output of one cultivation on the soil-restoration input of the other, in the same or neighboring "old" soil, creating a closed loop resource cycle as opposed to the two separate bio-waste cycles that are currently described by most of the available phytoremediation and essential-oil literature.

1. Industrial Effluent
(Textile, tannery, electroplating, mining, pharmaceutical, chemical, food processing, pulp & paper)

↓

2. Preliminary / Primary Treatment
(Screening, sedimentation, limited physicochemical pretreatment)

↓

3. Lemongrass-Based Phytoremediation System
(Soil-bed / constructed-wetland hybrid or controlled wastewater irrigation)

↓

4. Water Purification
(Phytoextraction, phytostabilization, rhizofiltration, rhizosphere microbial action)

↓

5. Reuse of Treated Water
(Irrigation, industrial process water, controlled discharge)

↓

6. Biomass Harvesting
(Rotational, multi-cut perennial harvest)

↓

7. Essential Oil Extraction
(Steam distillation)

↓

8. Biochar / Compost / Energy Recovery
(Pyrolysis of spent post-distillation biomass)

↓

9. Soil Restoration
(Biochar and compost applied to degraded or remediated land)

↓

10. Circular Economy → Environmental Sustainability
(SDG 6, 12, 13, and 15 alignment)

Figure 1: Integrated Sustainable Lemongrass System Technology for Industrial Effluent Treatment, Water Purification, and Soil Restoration

Note. Arrows indicate primary process flow; the system operates cyclically, as restored soil and reused water support subsequent cultivation and treatment cycles

This closed loop system is what puts the Sustainable Lemongrass System Technology framework in the principles of circular economy instead of the linear treat and release approach of most traditional wastewater management and contaminated-biomass management systems. As a whole, wastewater management has been specifically mentioned in Sustainable Development Goal 6, Clean Water and Sanitation, and Goal 12, Responsible Consumption and Production; nature-based solutions in this field emphasize the recovery of water, nutrients and energy from a 'waste stream' – as opposed to mere efforts to minimize waste treatment costs – with the carbon-sequestration and reduced-energy-input characteristics of plant-based, mostly gravity-fed and solar-driven systems contributing also to SDG 13, Climate Action. Although the existing literature has already proven efficacy of phytoremediation for Section 3, pollutant removal for Section 4, soil-restoration mechanisms for Section 6 and water-purification performance for Section 5 for lemongrass, the framework proposed herein moves to a synthesized and deployable system concept from the separate information found in the aforementioned sections.

This design has several sustainability benefits, in addition to the pollutant-removal benefit typical of all phytoremediation methods. There is "triple recovery" – water can be recovered and reused as a commercial and marketable product (treated effluent); essential oil can be recovered and applied to a variety of other fields; biochar and compost can be recovered and used to improve soil. Economics is thereby enhanced relative to schemes for phytoremediation without marketable products, as in principle a fraction of the value of the essential oil generated can be used to offset a part of the expenses of setting up and working the system, even if this application of the economics of the offset has not been, to-date, meticulously quantified in the literature reviewed, as reported further in Section 8. Applications of the technology indicate climate-relevant co-benefits, such as carbon sequestration or in living biomass and carbon sequestration via biochar soil amendment and energy savings from not needing to implement a previous (physicochemical) treatment step when achieving the same degree of pollutant removal.

In practice this ten-stage architecture can be viewed as more of a conceptual system flow chart, because the beneficial impacts of this solution are all reoccurring over successive harvests – restored soil can support much longer timeframes of continued or renewed lemongrass cultivation, purified and reused water can support subsequent irrigation cycles and essential-oil and biochar revenue generation will feed into the ongoing economic drivers of system operation.

It's worth stressing, when introducing this framework, its status as evidence. The present available literature has not yet been found to perform any single study testing the full ten-stage framework as an integrated whole, but rather each stage is proved by primary research—related to biochar derived from that medicinal crop or not—and cited throughout Section 2–6; while similar studies that provide evidence for the major biochar-to-soil-restoration loop and for the treated-water-to-reuse pathway are also cited, but related to a medicinal crop other than lemongrass or to general wastewater re-use rather than to wastewater derived from lemongrass distillation and specific re-use experiments on lemongrass. The Sustainable Lemongrass System Technology framework proposed herein should be read in that light; as an empirically informable synthesis and testable hypothesis for future field-scale research; not as an empirically validated, field-proven technology, a distinction that this paper does make explicit, but is re-emphasized in the concluding discussion of research gaps in Section 8.

8. Challenges, Limitations and Future research

Although the integrated framework outlined in Section 7 is coherent, several problems of substance need to be resolved before systems based on lemongrass could be taken from pot-culture and lysimeter evidence to validated field-scale deployment.

The most immediate limitation is the threshold limit of the toxicity of heavy metals. Across all the dose-response evidence summarized in Sections 3 and 4, an inflection point can be identified where beyond this chromium concentration (typically ~10–100 milligrams per kilogram) a decline in lemongrass growth and biomass accumulation, and thus remediation capacity and essential-oil yield, becomes detectable (Khilji & Sajid, 2020; Patra et al., 2018). This implies that systems using lemongrass are suitable only for the treatment of a wastewater and land contaminated to a lesser or a moderate extent and should be used after a first or primary stage of physicochemical reduction of the most polluting waste streams, an aspect that is often not emphasised in optimistic secondary/ popular-science literature on phytoremediation.

The second challenge is biomass disposal and post harvest management which are closely related. Phytostabilisation occurs with a phytostabiliser such as lemongrass; the majority of the accumulated metal is in root material which in most cases is not considered to be harvested, thus alleviating, but not eliminating, the problem of contaminated-biomass disposal in phytostabiliser-based systems. However, established post-harvest management literature highlights (aerosol) metal recovery, composting, pyrolysis, gasification, and torrefaction as possible pathways where a root system will eventually be disturbed or replanted or where values of loaded aerials biomass are measurable, while cautioning against potential re-release of the sequestered metals back into the environment through natural decomposition if not managed post-harvest and against transport costs for high biomass values, which can affect the overall economic viability of the remediation programme if such costs are not accounted for from the beginning (Khan et al., 2023). Where biomass enriched with metal does occur, economic value has the potential to be restored by the metal recovery scheme based on the mechanism of hyperaccumulator, as was achieved in other hyperaccumulator systems (Sheoran et al., 2009, Robinson et al., 1997) but has not yet been explored for lemongrass.

The challenges for scale up and field-implementation arise as a direct consequence of the majority of the evidence base synthesized in this review having been obtained from pot-culture, lysimeter and/or small-plot in situ trials, mostly in India and other South Asian countries. Little evidence exists to date to verify field scale performance of lemongrass under changing climate conditions, heterogeneous contamination gradients, uncontrolled hydrology, and operational conditions over multiple years compared to the much larger, field validated evidence base for conventional constructed-wetland macrophytes. To fill this gap, multi-year field trials are required, involving pollutant removal alongside measurement of essential-oils yield and quality, biomass generation, and soils parameters, and that has not been done so far in a single published paper.

Economic feasibility is not necessarily a decided question on the evidence reviewed here. Although the most convincing part of building a remediation system that produces essential oil and biochar from lemongrass would seem straightforward, no work reviewed in this study performed an in-depth techno-economic or full life-cycle cost analysis of an entire integrated system that relies on lemongrass, like those that have been completed for constructed wetlands (CWs) and for physicochemical treatments. Therefore, in order for the proposed system to be classified as a economically viable system, the cost of essential-oil and biochar revenues needs to be considered and determined whether they can realistically cover system establishment, land, labor, and processing costs and within what payback period.

Another practical constraint is regulatory and food-safety oversight. While this - it is non-edible - significantly minimises risk of contamination to the food chain, essential oil intended for the food-flavouring market and as feed for cosmetic and pharmaceutical uses is still subject to food quality and safety standards, limits on residue of heavy metals have not been standardised or enforced in all the territories that produce and export the product. Future regulatory-science research is similarly poorly developed in the current literature and a clear priority is long-term monitoring protocols, sensitivities of plants to soil contamination and tolerance to metals carried by oil over multiple growing seasons. Likewise, there is still limited interest specifically on the use of lemongrass for the phytoremediation of arsenic and mercury compared to overall literature on the phytoremediation of arsenic and mercury (Vithanage et al, 2012); and against the general known limitations of phytoremediation, related to root depth, identified in existing technical guidance (United States Environmental Protection Agency, 2000).

One of the more promising direction identified from the literature studied was opportunities for microbial-assisted phytoremediation. In the search for bacteria to promote vegetative growth for the purpose of soil bioremediation, plant-growth-promoting rhizobacteria (PGPB) have already been demonstrated to promote vegetative growth and to increase the accumulation of metals (mg kg-1) in mine-tailings trials (Ma et al., 2011). Agrobacterium-based generalist inoculants should be avoided, and focus should instead be on systematic screening of rhizobacterial strains optimized for specific lemongrass–metal combinations as well, which is likely a more attainable near-term research priority.

These findings indicate that lemongrass-based biological polishing should not be seen simply as a stand-alone alternative to conventional treatment methods, but rather should be combined with preliminary treatment of the most concentrated load fractions by physicochemical means and biological polishing of the not so concentrated load fractions by lemongrass. Optimized constructed-wetland hydraulic design for Cymbopogon specifically, is also essential engineering research, as it is quite different from the emergent aquatics upon which most of the above-mentioned design guidance for constructed wetlands has been based.

Lastly, extensive LCA is mentioned in the wider works on phytoremediation as a much-needed but yet underutilized decision support tool for assessing the overall footprint (including transport, processing, and end-of-life handling of the biomass) of phytoremediation-based systems versus other systems (Khan et al., 2023). It does not seem like any LCA study specific to a system integrated with lemongrass was found during this review; perhaps the single most valuable future line of research would be to find an LCA able that would quantify carbon sequestration, the treatment chemicals that would be avoided, the water saved by reuse, and the emissions generated by the production of the biochar and the distillation of essential oils. Finally, there is the possibility of genetic and agronomic improvement of cultivars for specific use in phytoremediation, similar to the improvements that have been bred into other phytoremediation crops for increased metal tolerance and biomass, but with a caution weighing on studies of any genetically modified or intensively bred cultivar that may be intended for use in a commercial essential-oil supply chain.

9. Conclusion

The peer-reviewed evidence related to lemongrass, Cymbopogon citratus and C. flexuosus, as one of the technologies that can be used in integrated treatment of industrial effluent, water and soil pollution has been synthesized in this review. Out of the literature reviewed, three conclusions can be drawn with some consistency. Lemongrass has a number of characteristics as an agronomically suited plant for a phytoremediation role: Firstly, it is fast growing; secondly, it is tolerant to wide range of pH and temperature; thirdly, it is noneatable; fourthly, commercially valuable regardless of remediation function, as the essential oil it produces contains heavy-metal content within permissible limits in conditions of moderate contamination; fifthly, it is not edible and it does not enter food chains, avoiding this risk of food-chain contamination. Second, lemongrass was found to have a dominant and strong mechanistic mode of phytostabilization rather than phytoextraction here; indeed, in all the studies conducted here on red-mud, fly-ash, tannery-sludge and mine-tailings, the plant invariably accumulated the bulk of metal in the root component, simply stabilizing contaminants in place rather than extracting them physically, with implications for how the success of remediation should be measured and communicated. Third, the capacity of the lemongrass to grow and to remediate also diminishes at concentrations beyond a moderate level, suggesting that rather than a treatment technology for highly polluted industrial effluent, it should be used as a secondary (polishing) remediation method for moderately polluted effluents and land.

The paper, based on this evidence base, has proposed a novel, literature-based integrated framework, called the Sustainable Lemongrass System Technology that contains and links together preliminary effluent treatment, lemongrass used in phytoremediation, water purification and reuse, biochar and compost to restore soil and harvest biomass, and the extraction of essential oils. The main novelty of this framework is concept synthesis – it brings together the evidence hitherto found: separately in literature on phytoremediation; essential-oil-economics; and post-harvest biomass-management, and puts it together in a circular-economy structure with a clear link to pertinent Sustainable Development Goals.

The practical implications are important for regions, mostly in South and South-East Asia, where most of the underlying evidence comes, which include the combination of an industrial effluent burden coupled with water scarcity, degraded agricultural and mining land and the fact that there is already infrastructure to grow and process lemongrass. The proposed framework is presented as a low cost and commercially co-productive alternative/complement to the use of conventional, physicochemical treatment for such regions. Meanwhile, this review has pointed out that the framework is presently a synthesized hypothesis that requires rigorous multi-year field trials along with techno-economic and life cycle assessment and specific testing of the less-established linkages to electroplating effluents, pharmaceutical effluents, as well as biochar-to-soil-restoration for lemongrass-remediated sites, before the system can be confidently scaled beyond the pot-culture and small-plot findings reported herein. These are obvious and most important avenues for future research.

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