Multiple applications of vetiver grass – a review

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Abstract: Since ancient times, vetiver grass and its roots are well known for their fragrance, medicinal and soil erosion control properties. Native to India, vetiver is a perennial grass that grows up to 2 meters in height and the roots grows up to 3 meters deep. They can grow in harsh conditions with limited water availability or in drought conditions. The roots hold plenty of soils, which encourages using this grass as a soil conservation tool in erosion prone areas. Several soil conservation sites have been successfully implemented using vetiver grass in several countries such as Haiti, Philippines and Thailand. In addition, the aromatic oil present in the roots of vetiver is used in perfumery and holds a very high commercial value. On the other hand, several research studies over the past years prove that vetiver grass could be used in other applications such as bioremediation of toxic wastes, farm hedges, termite control, household handicrafts, composites and herbal medicine. This work presents a compilation of research studies related to vetiver applications, policy recommendation, limitations and potential large-scale applications.

Key-words: vetiver grass, soil conservation, phytoremediation, energy, fragrance, medicine

1. Introduction

Vetiver grass is the common name for *Vetiveria zizanioides* and *Chrysopogon zizanioides*, an herbaceous graminaceous perennial type of plant with origin in tropical and subtropical India, South and South-East Asia [1]. During the last decades, vetiver grass has been widely spread throughout the equatorial region but also to other distinct parts of the globe due to its interesting properties. Various authors have described vetiver grass as a fast growth and low cost plant, which is highly resistant to drastic climatic changes, fire and pests, and tolerant to different types of soil, wide pH ranges (3.3-12.5) and high concentrations of micropollutants [2-5]. Vetiver grass roots are the source of the 'khus' essential oil, product highly used in perfumery and cosmetic markets [6]. Besides the relevant uses of vetiver oil, vetiver grass has been studied for other many relevant purposes in various contexts and countries such as India [7-10], Thailand [11-13], China [14, 15], Malaysia [16, 17], Burkina Faso [18], Ethiopia [19], Nigeria [20-22], Brazil [23-25], Venezuela [26], Haiti [27] and USA [28-31]. The countless applications of vetiver grass are reviewed in the current paper.

Regarding the vetiver plant features, the root system is composed of an extensive, dense and fast growing network of fibrous filaments that can reach depths of 3 m [1, 28]. The deep roots allow vetiver to grow in slopes, increase water infiltration rates and provide the desired grip action to reduce the chances of soil layer slippage in the occurrence of intense rainfall [2, 18, 32]. Vetiver has been effectively implemented in Africa, Asia, Australia, Central America, Latin America and southern Europe for stabilization of roads and railways artificial batters [2]. Soil and water conservation strategies with vetiver grass are discussed in section 2.1. Moreover, vetiver root system is naturally able to establish a symbiotic association with soil microorganisms creating a rhizosphere microenvironment in its surroundings and promotes the carbon fixation in the soil [8, 33]. At the rhizosphere level, vetiver is capable to accumulate substances that are normally toxic for other plants and living beings, such as heavy metals and petroleum. The capability of vetiver to decontaminate soils and water bodies has been largely studied [33]. The major target pollutants and vetiver phytoremediation strategies are reviewed in section 2.2. Moreover, due to particular compounds existing in vetiver roots, the plant has been used for pests control in the agriculture fields, as it is described in section 2.3. A key characteristic of the vetiver root is the high content in essential oil, known for applications in markets such as perfumery and pharmaceuticals, as it is summarized in section 2.6. Concerning the upper-plant characteristics, vetiver grass leaves are 0.5 to 1.5 m long, rather stiff and mainly composed of cellulose, hemicellulose and lignin [1]. Vetiver leaves biomass can be used for the production of natural fibers and other structures with application in households [34, 35]. Vetiver is considered a very interesting renewable feedstock for bioenergy production due to its typical high biomass growth rate [4]. The applications of vetiver grass leaves in household materials and energy production are explored in sections 2.4 and 2.5. Additionally, other applications of vetiver grass are presented in section 2.7. Due to the wide range of applications of vetiver grass and the recognized benefit for the populations, the plant has been proposed as a tool for environmental, economic and social growth and development. The authors have scrutinized the positive and negative arguments related to vetiver cultivation, presenting the main drawbacks, and have offered recommendations for policy-makers targeting vetiver grass expansion and better practices.

2. Vetiver grass applications

2.1 Soil and water conservation

Soil erosion and water runoff bring devastating effects on the environment and economy. Most of the time, soil erosion occurs due to severe flooding in the winter season or due to strong wind or flash floods in summer [36]. Most of these occur in the developing nations due to poor infrastructures and unfortunately during natural disasters such as earthquake and hurricane. On the other hand, population growth has increased the energy demand for cooking and household activities. This demand is met through forest fuels such as fuelwood and charcoal leading to deforestation in several developing countries. Though forest fuel use can mitigate climate change compared to fossil fuel, risk of soil erosion is high in case of deforestation, without counting a possible negative carbon balance. In addition, climate change has altered the pattern of rainfall, storm and drought around the world that has an impact on soil erosion. Furthermore, development of infrastructures such as residential buildings, dams and industries has influence on soil erosion. During soil erosion, vast amount of soil and water is displaced from the fertile fields to rivers that need to be cleaned [37]. While doing so, they end up in places where they are not needed thus wasting most of the economy and nutrients. The most common effects that occur due to soil erosion crises are the followings: soil loss, soil quality degradation, food production loss, habitual change for several organisms, economical burden to refill the soil and to remove the soil from the water ways. Some consequences are economic burden and environmental pollution due to fertilizer application to compensate the lost soil nutrients and high risk of natural disasters [36, 38, 39]. In addition, remedial actions require energy that adds up to the climate change through more greenhouse gas release. Therefore, affordable and easily executable soil erosion control measures are much important to the society.

Soil erosion control, soil and water conservation can be implemented through various measures. Vetiver plantation in erosion prone, earthquake and hurricane areas could be a promising viable option to control soil erosion and its detrimental effects. Several studies have proved the viability of vetiver in soil and water conservation. Babalola et al. (2007) reported that use of vetiver grass strips and mulch benefits soil conservation along with increasing the nutrient and water uptake efficiency of the soil [20]. Mickovski and Van Beek (2009) showed that vetiver plated in modelled terraced slope presents higher slope stability than the one of a non-vegetated slope [40]. Vetiver plantation also exhibited higher potential for resource conservation and increasing the crop productivity compared to lemongrass. However, their potential was lower than Sambuta grass under the sub-humid conditions [41]. Vetiver plantation for soil conservation has become familiar among Haiti famers. Recently 900 farmers have taken part in a vetiver plantation and management program Agri-plus conducted by a volunteer organization [42]. Cao et al. (2015) conducted runoff simulation experiments using three varieties of grass on a slope [43]. The study concluded that all the grasses were able to control the soil runoff effectively in the manner, Bahia grass (0.12 m/s) followed by vetiver grass (0.17 m/s) and daylily (0.19 m/s), and irrespective of the hedge widths the soil loss was minimized due to the grass stem features,. Furthermore, hedges with two-row were adequate to soil loss control. The laboratory tests conducted by Rahardjo et al. (2014) proved that vetiver grass is suitable as slope cover promoting slope soil effective cohesion [32]. It was shown that vetiver grass is able to minimize the loss of matric suction, increase the soil shear strength during rainfall and thereby maintain the stability of the slope. In a similar study, Eab et al. (2015) reported the slope stability through vetiver cultivation using shear, centrifugal model, seeping and rainfall tests [44]. The authors justified the slope stability improvements based on the rapid growth of vetiver roots in bundles that can significantly increase the soil shear strength through mechanical reinforcement. Moreover, Meyer et al. (1995), McKergow et al. (2004), and Nasrin (2013) reported vetiver sediment trapping efficacy of 90% and 65% and 71%, respectively [45-47]. Somchai and Tingsanchali (2016) reported on vetiver plantation showing 42.4% and 53.7% improvement in soil and water conservation, respectively [48]. Similarly, Kidd et al. (2005) studies showed very positive for vetiver system (no soil erosion detected) compared to chemical ground modifier, Polyhedral Oligomeric Silsesquioxanes (POSS) in earthen level systems [49]. As a strong evidence, Truong et al. (2008), Islam et al. (2013) and Boonyanuphap (2013), demonstrated the use of vetiver system at pilot scale for soil erosion prevention in Vietnam and concluded that vetiver is an environmentally benign sustainable bioengineering tool that is very effective, economic, social-based to protect infrastructure and mitigate natural disasters [50-52]. Once established, the vetiver plantations will last for decades with little maintenance [50]. In a recent report from Diyabalanage et al. (2017), a 4 to 6 km^2 vetiver plantation in Sri Lanka showed promising results in soil erosion control and water runoff [53]. Similar results were obtained in Wenago District, Southern Ethiopia [54]. In contrast to these studies, Hellin and Schrader (2003) reported that vetiver plantation has little impact in soil loss conservation for slopes greater than 33° [55]. However, only single row hedges were used in their experiments in maize field. From the literature study on soil conservation using vetiver plantation, overall vetiver seems to be a cheap and viable option for soil erosion for fields with slope less than 33◦. However, more experiments in real field trails at pilot scale are necessary to demonstrate the full potential of vetiver to control soil erosion.

2.2 Phytoremediation

Phytoremediation is generally a cheap solar energy driven technique which consists on the use of green plants to clean contaminated soil, sludge, sediments, natural groundwater and surface water. Various forms of pollutants can be assimilated, accumulated or even degraded by plants, from heavy metals to organic wastes. Vetiver has been proved to have great potential to be used as a phytoremediation instrument. The reported types of phytoremediation with vetiver plant correspond mainly to (1) phytoextraction (or phytoaccumulation) – accumulation of contaminants in the root and shoot areas of the vetiver plant [23, 24, 29, 33]; (2) phytostabilizazion – plants are capable of reducing the mobility and transport of heavy metals by keeping them in the rhizosphere microenvironment [33, 56, 57]; and (3) phytodegradation – once the contaminant molecules are taken by the plant, vetiver is able to break them down throughout the metabolic pathways of the plant [30]. Moreover, studies have shown that vetiver plant can be quite effective if it is directly implemented in a contaminated soil or applied simultaneously with soil amendments such as fertilizers, microbial consortiums, bulking agents, among others. The present subsection comprises a wide review on the studies performed so far with vetiver, including a discussion of its potential as an environmental remediation tool.

2.2.1 Heavy metals phytoremediation

Phytoremediation is considered an innovative, economical and environmentally compatible method for heavy metals remediation [58]. Land and water bodies surrounding mines in semi-arid and arid zones are very much vulnerable to heavy metals pollution [5]. Abandoned mine sites are another example of areas that require rehabilitation and decontamination of the soils. Nirola et al. (2016) have addressed the problems of toxic heavy metal pollution and reviewed several plants that can be used for phytoremediation, including vetiver plant [5]. The authors showed that vetiver plant is an effective accumulator of metals like Cr, Pb, Ni, and Zn. Antiochia et al. (2007) performed short and long-term phytoaccumulation experiments for several heavy metals (Cu, Cr, Pb and Zn) [58]. For all the test, the heavy metals are accumulated in roots, rather than in the shoots. The authors confirmed the efficiency of vetiver as a particular hyper-accumulator for Pb and Zn, however, with relatively low heavy metal uptake rates for bioremediation purposes [58].

Furthermore, Ar, Cd, Hg and Ni can be extracted by vetiver plant, where the largest accumulation occurs in the roots (>70% of the total amount of heavy metals accumulated) showing low translocation from the roots to the shoots [33]. Within this group of heavy metals, the scientific community has payed greater attention to Cd since it is a very common contaminant in agriculture fields, which can easily get to humans and livestock directly via the food chain [57]. Vetiver was found to be useful for phytoextraction and phytostabilization of low and moderate Cd field contamination, reducing the risk of food chain pollution [15]. Phusantisampan et al. (2016) have proved vetiver's tolerance to high soil Cd levels, and have found that the plant can mainly accumulate Cd in its roots [57]. The enhancement of the soil quality through the addition of amendments (e.g. pig manure) can increase vetiver plant growth, support the survival of the plant in harsh Cd contaminated soils and improve its phytostabilization potential [57]. Other studies have evidenced the positive outcome of the use of soil amendments in heavy metals phytoextraction and phytostabilization by vetiver plant [23, 24, 59].

2.2.2 Carbon-based compounds phytoremediation

The current subsection features a review on the use of vetiver plant as a phytoremediation tool for carbon-based compounds-contaminated soils. Vetiver plant can tolerate crude-oil-contaminated soils, and it is able to grow and improve the soil quality [26]. However, besides the high tolerance to adverse toxic environment, vetiver plant growth and root system development are negatively affected by the hydrocarbon contaminants, which makes the plant less suitable to biodegrade the pollutants. Therefore, vetiver is proposed as an alternative for soil quality enhancement, erosion control and, thus, prevention of contaminants surface spreading [26]. (2006). Furthermore, Nanekar et al. (2015) have studied the use of vetiver plant in a microbe assisted phytoremediation system for crude oil sludge treatment [59]. Within a phytoremediation system composed by a microbial consortium, a bulking agent and nutrients, vetiver plant has enhanced the treatment due to rhizodegradation.

Another interesting application of vetiver is related to the treatment of 2,4,6 trinitrotoluene (TNT)-polluted soils. TNT has been identified as a carcinogenic substance, commonly present in explosive-contaminated areas. Das et al. (2010) revealed that vetiver grass is capable of removing TNT from soils pretreated with urea chaotropic agent [29]. Additionally, Das et al. (2015) have investigated TNT removal effectiveness of vetiver-urea system at its recommended concentration for agricultural purposes [30]. TNT and TNT-derived metabolites were observed in vetiver grass roots and shoots, which proves the capability of vetiver to translocate TNT from the root system to the aerial parts and to degrade TNT. In detail, 1,3,5-TNB, 2-ADNT and 4-ADNT metabolites have been found in the shoot tissues proving its ability for TNT phytodegradation [30]. Finally, Das et al. (2017) suggested that TNT degradation is related to the activity of nitroreductase (NR) enzyme, which is induced by increasing temperature up to 35°C and TNT concentrations until a maximum of 40 mg L^{-1} TNT [31]. This study contributes to an effective design of the TNT phytodegradation system using vetiver plant.

Phenol is a pollutant frequently occurring in industrial effluents from petro industries, coal conversion units, and fungicide, herbicide and insecticide industries. Singh et al. (2008) found vetiver can effectively remove phenol and, through biochemical mechanisms, it is able to develop resistance to reactive oxygen species the production of which is induced by the presence of phenol [60]. More recently, Ho et al. (2012) showed the potential of the application of functional endophytic bacteria to enhance vetiver plant's efficiency for phytoremediation of phenolic pollutants [61].

Polycyclic aromatic hydrocarbons (PAH), e.g. benzo[a]pyrene, can be found in coal tar and tobacco smoke, and are formed from the incomplete combustion of organic materials [62]. These compounds are widely spread in the environment and represent a danger for human health since they are considered carcinogenic. PAH can be degraded by certain microorganisms and, therefore, enhancing the development of particular microbial communities in contaminated soils can be promising for bioremediation [62]. To illustrate this, Li et al. (2006) showed that vetiver grass is able to accelerate the dissipation of benzo[a]pyrene in water by increasing the microbial activity in the rhizosphere soil [63]. Nisa and Rashid (2015) recently investigated the phytoremediation effectiveness of vetiver plant in a diesel-contaminated soil by PAHs (including benzo[a]pyrene). It was found that vetiver is able to undertake PAH [64]. Nevertheless, the translocation of PAH from roots to shoots is limited particularly for benzo[a]pyrene. The authors concluded that vetiver phytoremediation is a viable choice for PAH decontamination, given enough time for plant establishment and contaminant degradation [64].

Ethidium bromite, a substance commonly used for DNA-staining in electrophoresis is considered highly mutagenic and toxic. Vetiver grass was proposed for phytoremediation for such compound due to its ability to uptake 0.7 µg of ethidium bromite per kg, high biomass production and rapid growth rate [33]. Another example of a highly toxic contaminant is acrylamide, building block for polyacrylamide gels, commonly used in DNA and RNA analysis. Polyacrylamide presents no harmful effect in the environment, however, it can be degraded into acrylamide, a carcinogenic and neurotoxic compound that can contaminate water and soil [65]. Vetiver plant was investigated for the treatment of acrylamide-contaminated soils. Paz-Alberto et al. (2011) proved that vetiver is very tolerant to such pollutant, capable of massively up-taking acrylamide from the soil due to its long, dense and extended root system [65].

2.2.3 Wastewater treatment strategies

Vetiver proves to be efficient in reducing biochemical oxygen demand (BOD) and enhancing total nitrogen (TN) and total phosphorus (TP) removal from wastewater [3, 17, 25]. Boonsong and Chansiri (2008) demonstrated that vetiver grass has high survival rates in high concentration domestic wastewater and that the highest BOD, TN and TP treatment efficiencies occur at the highest concentrations of pollutants [3]. Vetiver grass is shown to be promising for in situ domestic wastewater treatment [3]. Moreover, Chua et al. (2012) investigated the performance of vetiver grass in a floating wetland system for treating urban runoffs [66]. The average nutrient uptake rates (mg day^{-1} m^{-2}) with vetiver grass were 1.74 and 0.16 for TN and TP, respectively. Furthermore, Darajeh et al. (2016) demonstrated the effectiveness of a vetiver grass floating system in the treatment of palm oil secondary effluents [17]. The results have shown an impressive decrease in organic matter of 96% (BOD), proving vetiver system as an innovative, cheap and efficient tool for organic matter removal of these kind of effluents. Moreover, Ramos et al. (2017) recently evaluated the pollutant removal from swine wastewater in horizontal-flow constructed wetlands using vetiver grass [25]. The authors estimated organic matter, TN and TP removal efficiencies of 81, 36 and 45%, respectively, which are quite satisfactory and close to other plants used in this kind of treatment. Moreover, vetiver can be used to treat heavy metals-contaminated water systems [1]. For instance, the removal of heavy metals from wastewater was studied by Singh et al. (2015), using a batch scale floating platform [10]. The authors showed optimum growth of vetiver at a pH 6-9 and effective removal of Pb and Cr, ranging from 80 to 94% for Pb and 77-78% for Cr. As another example of vetiver application in wastewater with heavy metals, Sobahan et al. (2015) presented a successful 2-step process for heavy metal phytoremediation involving vetiver grass [16]. A two-step wastewater treatment technique was proposed comprising, in the first stage, a *Pseudomonas aerogionosa* bioreactor and, in the second stage, vetiver grass cultivation. At the first stage a large part of the contamination is removed, which results in lower heavy metals concentrations and toxicity in the second stage, allowing improved vetiver's growth rate. The two-step process was more efficient than a direct only vetiver treatment [16].

2.3 Agriculture

2.3.1 Soil quality enhancement

Vetiver grass reveals to be an interesting plant-based agro-tool for soil quality enhancement. In fact, besides the environmental quality it advantages, the utilization of vetiver grass as a tool for soil and water conservation (section 2.1) can directly improve agro-practices. Vetiver grass may be intercropped within other plantations in order to improve agriculture soil structure and stability, avoid soil erosion and increase field's permeability to water, elements that can lead to enhanced growth and higher crop productivities in the target fields. In fact, Yaseen et al. (2014) reported that intercropping is required to sustain the productivity of vetiver grass essential oil when the available land resources are [9]. Since vetiver industrial crop is planted with wide row spacing and presents a slow growth in the first 2-3 months, infestation of weeds may occur in the inter row spaces. Therefore, land productivity can be improved by introducing complementary and well-suited fast growing crops in the inter row spaces. Land use efficiency increased 130% for the vetiver-sweet basil-radish-*T.minuta* intercropping system, and 35% higher net return is obtained compared to sole crop of vetiver [9]. Another example is given by Babalola et al. (2007), who studied the vetiver grass strips and mulch effectiveness in soil conservation and maize agricultural yields improvement. It was found that vetiver mulch lead to higher grain yields, while vetiver strips helped for higher effectiveness in reducing runoff and lowering soil losses [20]. Therefore, Babalola et al. (2007) proposed to combine vetiver grass strips and vetiver grass mulch in the field in order to achieve better yields and soil, water and nutrients conservation [20]. Moreover, Sujatha et al. (2011) studied the feasibility of intercropping vetiver grass in arecanut (*Areca catechu* L.) plantation in the context of organic farming in India [7]. According to Sujatha et al. (2011), vetiver-arecanut total system productivity equals 3231 kg ha^{-1}, considerably larger than the average productivity of arecanut in India (1400 kg ha^{-1}) [7]. Lastly, vetiver intercropping leads to an increase in the resource use efficiencies and net return per unit area [7]. Furthermore, Oshunsanya (2013a) evaluated the effect of the spacing of vetiver grass hedgerows in soil accumulation levels and maize-cassava intercrop system yields. Soil accumulation levels were affected by the spacing between hedgerows: wider intervals lead to larger accumulation [21]. Additionally, both maize grain and cassava tuber yields were higher than the no-hedgerow control crops [21]. Moreover, Oshunsanya (2013b) investigated the effects of vetiver grass alleys in other crops such as okra, sweet potato and yam tubers [22]. Soil quality was improved due to the fallow and long-term effect of vetiver grass alleys placed within the plantation.

Likewise, vetiver grass phytoremediation can be used for agriculture soil decontamination in order to reduce the levels of pollutants and improve the performance of the crops. Several cases described in section 2.2 can be applied in the context of agriculture soil improvement. As an example, Dousset et al. (2016) provided with an interesting application of vetiver remediation in cotton fields and urban vegetable agriculture plots in Burkina Faso [18]. The effect of the use of vetiver hedges to reduce the concentration of micropollutants such as endosulfan and heavy metals (Cd and Cu) derived from urban solid wastes was investigated. Furthermore, vetiver leads to the reduction the micropollutants concentrations since it was able to degrade endosulfan and to accumulate large quantities of heavy metals in its roots. Lower micropollutant concentrations were verified in the shoots, which reveals to be beneficial since it prevents heavy metals from entering the ecosystem food chain [18]. Additionally, vetiver roots increased soil macroporosity and, consequently, the water infiltration rate in the soils, contributing to higher access to water by the crops. Concluding, vetiver edges can greatly improve soil and groundwater qualities, presenting advantages for cotton and urban vegetable crops in Burkina Faso [18].

2.3.2 Termite control

Termites are an example of serious plants menaces threatening agriculture producers and leading to huge losses of perennial crops [67]. Biological methods have been proposed for termite control as an alternative to the use of chemicals that lead to additional pollution and development of resistance by the target insects. Within the bio-based methods, the use of plant essential oils with insecticidal action has become popular. Vetiver grass oil, proved to be one of the most effective due to its long-lasting activity [67]. Various authors have proved the effectiveness of the oil present in vetiver's roots for termite control [28, 68, 69]. Additionally, nootkatone, compound existing in vetiver roots, is also capable to disrupt termite behavior [70]. The insecticide activity of both vetiver oil and nootkatone is associated to the toxic effect of such compounds in the protozoa present in the termite gut which are responsible for the termite's digestion. Such toxic effect progressively leads termites to starvation and death. Maistrello et al. (2001) found that vetiver grass oil or nootkatone sand pretreatment can significantly reduce the total length of the tunnels constructed by the termite *Coptotermes formosanus* Shiraki, when compared to non-treated or cedrene-treat sand [68]. Moreover, Nix et al. (2006) evaluated the effect of using vetiver grass roots as soil mulch to act against the same subterranean termites *C. formosanus*. In this study, vetiver root mulch (with a root to sand ratio of 25% in mass) proved to reduce termite tunneling activities/wood consumption and increased termite mortality [28]. One recent study performed by Van Du et al. (2015) proved that vetiver grass compost enhances cacao (*Theobroma cacao*) plant growth and contributes for termite control around such crop [69]. Besides the proven technical efficiency for termite control in various crops, Ewetola et al. (2017) investigated social acceptance and Nigerian farmer's perception on vetiver grass application for termite control [71]. The authors identified the necessity for the increase of the farmer's awareness regarding vetiver grass potential for control of termites.

2.4 Households

The use of vetiver leaves for household needs have been practiced since earliest time in several parts of the world. Due to the development of new materials and modernization, vetiver-based construction materials have been slowly replaced. However, these modern materials are blamed for larger climate change impact and pollution due to their energy intensive manufacturing process. In the recent years, more priority is given to climate change mitigating process and vetiver could be reintroduced in households. A new building material based on vetiver grass ash for use in the rural areas of the developing countries was experimentally investigated [34]. Vetiver ash revealed to have 7% higher silica content and seven times higher potassium oxide (K_2O) content than fly ash, being classified as class C pozzolana according to ASTM requirements. Thus, vetiver ash mortar can be used as a building material for sewers, foundations, marine infrastructures and also constructions under chemically exposure due to their higher resistance to acids [34]. A paddy storage silo at pilot scale (3 m height and diameter with 10 t capacity) was constructed utilizing vetiver grass and clay. Clay serves as matrix and vetiver grass as reinforcing fiber. Axial compression, flexural, shearing, tensile, bearing, and density of vetiver-clay bundle were proved to be adequate. The quality of paddy stored at the top, middle and bottom of vetiver-clay silo bin was shown to be unchanged in ambient temperature, relative humidity and moisture content tests [72]. Moreover, vetiver grass can be used as roof thatch in rural houses due to its wax coating and unique scent that presents water proof and insect repellent capacities. They are more durable compared to other type of grasses and are last long while used in steep roof compared to that of flatted roof [73, 74]. Recently, vetiver grass was explored for its use in ceramic production for replacing feldspar due to its high potassium and silica content. Thermal analysis revealed that vetiver grass can act as a flux agent at low temperatures (600°C) to form a glassy phase and can be an option for promoting environmental sustainability in terms of waste and mining reductions [73]. Furthermore, Ruksakulpiwat et al. (2007) reported vetiver grass use as a filler material in polypropylene composite [35]. Vetiver–polypropylene (PP) composites were prepared using injection molding with different vetiver contents and lengths, and their properties were studied. Larger vetiver contents lead to composite's viscosity, Young's modulus, heat distortion and crystallization temperature increase, and tensile strength, decomposition temperature, impact strength, elongation at break decrease. The mechanical and the impact properties were further improved by chemical and rubber treatment [35]. Lastly, as an interesting application of vetiver-derived products in households, vetiver oil could be used to treat wood against termite and wood borers attack. Coating wood with vetiver oil preserves the wood for long time [76]. With the increase in demand for more bio-products and climate change mitigation policies, research in vetiver-based composites is expected to increase in future years.

2.5 Energy

While using vetiver roots for improving soil structure and in some cases for decontamination, the upper part of the plant may be used as an energy crop. Different conversion techniques can be applied to valorize vetiver leaves biomass into biofuels, for instance, based on biological processes, thermochemical, biochemical or combinations of those. Vetiver leaves are made of lignocellulosic biomass presenting cellulose, hemicellulose and lignin contents of typically 32.6%, 31.5% and 17.3% (dry basis), respectively [77]. The biomass composition of the vetiver grass varies depending on its origin and ecotype [11]. Moreover, as presented in further sections, the oil present in the roots of vetiver grass plant has a high commercial value and it is frequently used in pharmaceutical, cosmetics and perfumery industries. Another alternative is to valorize the remaining parts of the vetiver roots (which comes from the vetiver essential oil extraction process) for the production of energy.

Bioethanol production from vetiver grass-derived sugars was reported by Rao et al. (2015) and Wongwatanapaiboon et al. (2012) [74, 11]. In order to produce bioethanol, first vetiver grass undergoes one or more pretreatment stages in order to improve the access to cellulose by cellulases, followed by an enzymatic process that hydrolyses cellulose fibres and forms simple sugars. Afterwards, the simple sugars can be further converted into ethanol through fermentation. Rao et al. (2015) reported 13% (w/w) ethanol/grass yield using alkaline pretreatment, cellulosic hydrolysis and fermentation [74]. Moreover, among another 18 types of grasses in Thailand, Wongwatanapaiboon et al. (2012) showed that the Sri Lank ecotype vetiver grass presented the highest ethanol production performance: 1.14g/L and yield of 0.14 g ethanol/g substrate [11]. The higher ethanol production efficiencies in this study can be justified since the authors performed the co-fermentation of glucose and xylose [11, 13]. Additionally, Raman and Gnansounou (2015) investigated the environmental impacts of a standalone bioethanol production system from vetiver leaves in the geographical context of India [77]. Greenhouse gas emissions and fossil depletion impacts of bioethanol were lower than the reference petrol system in 95% and 23%, respectively [77]. The authors highlighted the economic and environmental potential of the use of vetiver leaves in the context of multiproduct biorefinery platform, manufacturing bioethanol (from C6 sugars) and furfural (from C5 sugars).

Still within the biofuels application, Li et al. (2014) investigated the potential of producing biogas from the above-ground vetiver biomass in the context of ecological restoration of China [14]. Biogas was produced with a batch anaerobic fermentation and drainage collection process. The authors concluded that vetiver plant has a large potential to be used as a raw material for biogas production in China and that the biogas productivity can vary depending on the harvest period. Moreover, Crocamo et al. (2015) studied the production of biogas through anaerobic digestion from vetiver grass [4]. The use of the digestate from the digestion chamber (rich in nutrients) as soil amendment was also investigated. The authors found that specific methane production yield with vetiver grass was 650 Nm^3 against 510 Nm^3 per ton of total organic carbon for other common grasses. Additional tests have proved the effectiveness of us of the digestate as a fertilizer.

Due to the high biomass production, vetiver dried grass bunches are suitable also for the production of briquettes or pellets (ref 1). Briquettes or pellets are used as fuel, commonly for heat generation. Vetiver grass has a reasonable energy value of 16.3 GJ/t, compared to dry wood 19.8 GJ/t and sugarcane bagasse 9.3 GJ/t [78]. However, further research on vetiver foliage combustion must be performed in order to investigate, first, the impacts of vetiver combustion in terms of noxious compounds emissions, derived from vetiver's high nitrate absorption, and, second, the impact of silica on furnaces [78]. Meantime, the United Nations Environment Programme (UNEP) has published a report on feasibility assessment for implementation vetiver charcoal production enterprise in Haiti. The results showed that vetiver leaves performed very well indicating that leaves are a suitable energy source. In contrast, the use of vetiver root residues for production of green charcoal is proved to be inefficient due to the large quantity of dirt and sediments in the roots [79]. Nevertheless, Unikode enterprise located in Haiti is currently producing and commercializing briquettes utilizing vetiver including vetiver leaf biomass provided by the small holders and vetiver root biomass provided from vetiver oil distilleries [80].

2.6 Perfumery and medicinals

By 2022, the vetiver oil market is expected to reach USD 169.5 million globally according to Grand View Research [81]. From the early times vetiver oil has been produced locally and used as perfumes and medicine. However, only in the recent decades they are produced and marketed in industrial scale. Vetiver fibrous roots contain, in average, 1-3 % (dry weight basis) of oil. The crop oil recovery yield is reported as 10-30 kg of oil per hectare. Vetiver oil is largely produced worldwide, coming mostly from Haiti, Indonesia and India, with an estimated capacity of 300-350 tons/year [6]. The essential oil is typically obtained by steam distillation, leaving abundant root residues [27]. Vetiver oil is vastly appreciated for the formulation of high grade perfumes due to its woody, earthy and grapefruit odor. It is produced by distillation of vetiver using water or solvents. Vetiver oil has a huge structural diversity such as bicylic, tricylic sesquiterpenes, hydrocarbons, alcohol, and carboxylic acids, and excellent fixative properties that allow it to be used widely in perfumes and as the starting material for fragrance ingredients such as vetiverol, benzoic acid, furfurol, vetivone and vetivene [82]. Vetiver oil is mainly used for its dry woody base notes in perfumes and 250 kg of vetiver rool is used for producing 1 kg oil extract [83]. Approximately 10 % of the vetiver oil is conventionally transformed into vetiveryl acetate by chemical process and, recently, Notar et al. (2017) reported the environmental benign process for vetiveryl acetate using lipase enzyme catalyzed reaction of acetylation of alcohols [84].

Apart from its value in perfumery industry, vetiver oil is also used in cosmetics since the olden times. The vetiver roots are soaked in coconut hair oil to give fragrance and is still practiced in some rural parts of south India. In the recent years, the use of oil is wide spread in several cosmetic products such as soap, deodorants, lotions, shampoos and skin bleach. Vetiver oil is suitable for cosmetics due to its fragrance, low volatile additive characters and safety specifications [85-89]. Vetiver oil usage in cosmetics is expected to increase in future as consumers are demanding more sustainable cosmetics with natural ingredients [90].

Similar to its application in perfumes and cosmetics, vetiver oil is used as a medicine since antique time to treat dermatitis, hemorrhoids, fever, rheumatism, neuralgia, and fungal growth control [91-93]. In recent years, their application in medicine is supported by several research findings. Porras and Francisco (2002) received a patent for the invention relating the vetiver grass extract for increasing or restoring hair growth or preventing hair loss [91]. Another research study data suggests that vetiver grass oil has therapeutic potential for both cosmetic and metabolic health care products through bioactivity tests in a human skin disease model. Vetiver oil showed significant anti-proliferative activity, inhibited collagen III production, strongly modulated global gene expression and impacted several critical physiological processes signaling pathways related to tissue remodeling and cholesterol metabolism [94]. The effect of vetiver oil on tuberculosis was studied by Saikia et al. (2012) who concluded that vetiver oil was active against both virulent and avirulent strains of M. tuberculosis [95]. The vetiver root extract could be potentially an antituberculosis agent. Moreover, vetiver oil has been tested as a mosquito repellent along with other plant oils such as citronella, hairy basil and catnip. The results confirmed that vetiver oil could serve as potential mosquito repellent products against Cx. quinquefasciatus and An. minimus mosquitos. A similar study was reported for Malaria vector Anopheles stephensi, anti-inflammatory, anti-oxidant and anti/fungal property of vetiver oil [96-98]. Vetiver oil is also used in aromatherapy within hospice and palliative care for cancer patients since it can alleviate pains caused by cancer and decrease symptoms like chronic fatigue, pain, insomnia and anxiety [99].

2.7 Other applications

Vetiver gas cultivation could be a fire breaker in rural area where most of the fire starts from dry grass. As vetiver grass leaves are green and succulent even during the dry season, it prevents spreading of such fires. On the other hand with huge fires even if the grass burns, it roots remains intact and grass grows very rapidly [36, 73].

While vetiver is used for the above said applications, it indirectly contributes to carbon sequestering and favors climate change mitigation [100, 101]. The roots and the grass are rich in carbon and they can grow very fast with limited water and nutrients in most of the weather conditions. However, when the grass is cultivated for their roots without sustainable practice it could have a negative impact in the environment. Vetiver grass and roots could be a potential raw material for pulp and paper production due to its high cellulose content [102, 103]. Recently, Chandranupap and Chandranupap (2012) reported pulp production from vetiver grass with NH_4OH-KOH-AQ mixtures capable for making printing and writing paper [104]. In addition, from the large scale production of vetiver oil from its roots, a huge amount of lignocellulose residues are obtained that are suitable for activated carbon production [105]. Altenor et al. (2013) reported the activated carbon production with high surface area greater than 1000 m^2/g and up to 1.19 cm^3/g high pore volume to absorb phenol and methylene blue using vetiver roots as raw materials, steam and H_3PO_4 as activation agents [27]. Furthermore, both vetiver leaves and the remaining root lignocellulosic residues from vetiver oil industries may be considered for the production of biochemicals. Another interesting research field is the study of strategies for the valorization of the lignin fraction present in these residues.

Herbal drink is produced using vetiver grass [106, 107]. The herbal juice concentrate is commercially available from Usheera Industries Karnataka, India. In addition to these applications, vetiver can also be used in textile industry, mushroom cultivation, vermicomposting and manufacturing of food additives [12, 74, 92, 108, 109].

3. Policy recommendations and limitations

The above mentioned applications fall under three benefit groups, as it is summarized in Table 1. The current classification of vetiver benefits proves that vetiver cultivation has the potential to play a crucial role in economy, environment and social aspect around the world. However, its potential in large scale has not been achieved due to poor policy and the lack of promoting activities. Therefore, framing policies and implementing those policies are vital to harness all the benefits of vetiver.

Table 1: Economic, environmental and social benefits of vetiver grass cultivation.

Economic benefits	*Environmental benefits*	*Social benefits*
• Intercropping vetiver for improve land use efficiency and economic net return. • Pests control brings larger productivities and lower losses. • Vetiver oil for perfumery, cosmetics and medicine could generate good return. • House hold articles, herbal drink; mushroom cultivation will fetch additional income and increases the use of bio products.	• Soil conservation, decontamination and enrichment. • Water conservation, lower need for irrigation and water saving. • Groundwater and wastewater treatment. • Vetiver cultivation is an environmental tool for C sequestration, climate change and its damage mitigation.	• Food and water security by using vetiver to decontaminate soils and underground water. • Use in medicine applications and natural perfume improving the health and well-being of the communities. • Local development and higher agriculture stability due to the ability to grow crops more efficiently. • Increasing the employment and economic status of rural population. • Energy supply to rural population – improving energy security.

3.1 Policy recommendations

At the time being, only vetiver oil has been commercialized and other few applications (e.g. vetiver drink) have been implemented in large scale so far. Other applications are still in initial research scale or pilot scale, therefore, the policy framework should introduce several project funding in order to promote further research in vetiver cultivation and scale-up projects. The creation of partnerships between academia, private industries and non-government organizations should be promoted. New vetiver policy must comply long-term, self-supporting, non-disruptive (does not require large changes), efficient (leads to significant benefits at low cost), supportive (leads to benefits other than the main benefit), effective and implementable actions [110]. Accordingly, policy recommendations for vetiver cultivation and its application are provided in the following paragraphs.

Promoting vetiver cultivation and maintenance of the crops: the governments should come forward to: conduct workshops and know-how camps to increase and spread knowledge on vetiver and to rise the demand for vetiver-based products; provide subsidies to attract more farmers towards vetiver stand-alone cultivation and intercropping cultivation strategies; enhance agents capacity in technology application in order to facilitate and support farmers to adopt the technology [111]; organize land users groups favoring knowledge and benefit sharing; open several nurseries to have adequate vetiver saplings and seeds [111]; strengthen government services to encourage non-government organizations to regulate the maintenance of vetiver cultivation; regulate vetiver root harvest only in selected regions through income based licensing and quota process; set national level annual targets to implement vetiver cultivation schemes and maintenance; ; apply stringent quality control and regulation for vetiver application in medicine, food and cosmetics in order to prevent from the presence of toxic compounds due to the bioremediation features of vetiver.

Improving vetiver goods trading, partnerships and sustainability: improve supply-chain infrastructures towards effective logistics and transportation of vetiver in/outputs; generate cooperatives, linking several villages to ensure easy vetiver goods trading and quality monitoring; frame and implement new regulations to corporates buying vetiver to implement fair prices for the local producers and respect of indigenous rights; increase private industries partnerships by providing tax incentives; promote vetiver cultivation as a sustainability tool through international cooperation and collaboration involving developed and developing countries; provide financial incentives to private landowners and support public projects for government land to cultivate vetiver; implement vetiver cultivation in carbon credit programs to attract funding as vetiver plantation favors carbon sequestering; channel funds to life cycle and sustainability assessment studies in order to characterize vetiver cultivation for conservation purposes and other applications.

Encouraging vetiver research: implement supportive measures to use vetiver grass leaves for energy and biochemicals production, and increase the income of farmers and rural employment generation; initiate research to improve vetiver cultivation techniques for obtaining lower crop oil yields for conservation strategies and higher crop oil yields for perfumery application, e.g. by adding microbes to soil [112].

3.2 Limitations

Despite their vast application potential, vetiver cultivation and use have few drawbacks that need to be addressed carefully before its implementation at large scale. At present, the main goal of vetiver cultivation in many parts of the world is to utilize the roots to extract oil. When the roots are dug from the ground, the soil becomes more vulnerable to erosion leading to negative impacts. Therefore, if the purpose is to use vetiver for conservation purposes, stringent rules are required for vetiver cultivation and roots harvesting. Control measures should be implemented by the corporates to forbid collection of roots from such misuse. Government should also charge heavy fines for such collection and form several vigilant teams to check such actions. Since these measures would not be socially acceptable due to the necessity of strong and authoritarian governance, a scientific research option should be encouraged: develop species of vetiver grass with very poor oil content of the roots. In addition, the removal of the roots for oil extraction in the case of the conventional species must follow the rules drafted in the Natural Resources Stewardship Circle (NRSC). That includes: a) keeping the minimum age of the roots to 12 months and harvest in dry season; b) maintaining transparency along the supply chains; c) encourage ethics and fair trade; d) address the regional environmental issues where the crops are grown and long-term commitment [113]. Moreover, research on other means of vetiver cultivation for oil extraction has to be initiated to fulfill the future vetiver oil demand without affecting the environment. An example is to implement indoor cultivation techniques (LED based indoor farms) in waterways through plant biotechnology and tissue culture. Invasive varieties of vetiver should be completely avoided, diseases associated with vetiver should be identified and control measures applied to eradicate these diseases. Many rural parts of world prone to erosion are not aware of vetiver cultivation and its application still due to poor infrastructure, communication and financial issues. Such areas should be identified in order to introduce vetiver conservation projects through social improvement fund in collaboration with developed countries.

4. Conclusions

Research studies, conservation projects and commercial projects on vetiver cultivation prove that, vetiver has the potential to provide economic, environmental and social benefits in several rural parts of the world. Its long deep root, dense moist shoot, ability to thrive in extreme weather conditions with minimal maintenance, and use in vast application make this plant superior for conservation and rural development projects. However, in reality the real benefits of vetiver is not harnessed to full so far due to lack of appropriate policy measures and regulations, adequate funding and international collaboration. In addition, most of the vetiver cultivated is streamed only towards certain applications. Therefore, owing to its vast application and demand for natural soil erosion remedy, energy and bioproducts, several vetiver conservation projects that could be a win- win situation for both people and environment should arise in future. This could be achieved through collaborative efforts from the developed, developing countries. In addition, more research inputs and development of modern cultivation techniques and machineries are necessary to enhance the quality and applicability of vetiver.

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