Potential use of *Pennisetum purpureum* for phytoremediation and bioenergy production: a mini review

Nurul Atiqah Osman^a, Ahmad Muhaimin Roslan^{a,b*}, Mohamad Faizal Ibrahim^{a,b}, Mohd Ali Hassan^a

^aDepartment of Bioprocess Technology, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia (UPM), 43400 UPM Serdang, Selangor, Malaysia

^bLaboratory of Biopolymer and Derivatives, Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400, UPM Serdang, Selangor, Malaysia

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Abstract. Organic and/or heavy metal pollutants in soil and wastewater can be remediated by phytoremediation. Phytoremediation combines the disciplines of plant physiology, soil microbiology and soil chemistry. There are several ways by which plants extract, stabilize, filtrate, volatilize or degrade the contaminants. However, the effectiveness of phytoremediation relies upon the type of plant used. *Pennisetum purpureum*, commonly referred to as Napier grass, is one of the exceptional phytoremediators due to its rapid growth rate and ability to survive in highly contaminated soils. In the present review, the potential use and applicability of *P. purpureum* to remediate various contaminated areas was highlighted and comprehensively discussed, especially the five phytoremediation mechanisms involved (*i.e.*, phytodegradation, phytoextraction, phytofiltration, phytostabilization, phytovolatilization). The application and management of *P. purpureum* in soil and wastewater phytoremediation were also critically presented. The coupling of phytoremediation and bioenergy is the zero-waste concept that can be applied since *P. purpureum* contains high lignocellulosic content that can be utilized as carbon source for biofuel production, such as ethanol and butanol.

Keywords: Napier grass, phytodegradation, phytoextraction, phytofiltration, phytostabilization, phytovolatilization

INTRODUCTION

Most human activities including household, agriculture and industry produce large volumes of wastewater. In most cases, the wastewater goes untreated and is released directly to the environment. As water usage increases, so does the wastewater and as a consequence, the pollution load also increases. This in turn will negatively affect both human health and the ecosystem (WWP, 2017). However, the path towards solving this problem is a complex one; there are varying types of pollutants and pollution strengths of the wastewater, thus, an effective

treatment system should take this into account. What is more, rapid urbanization and industrialization, as well as thriving agricultural activities, have also impacted on the soils integrity. Various hazardous and toxic pollutants from these activities will contaminate the soil. The recalcitrant nature of these pollutions is a serious threat to the environment and human health. Therefore, it comes as no surprise that the management of contaminated soil has become a great priority in developed and developing countries, which in turn, help support their

*Author for correspondence: Ahmad Muhaimin Roslan, Department of Bioprocess Technology, Faculty of Biotechnology and Biomolecular Sciences, Universiti Putra Malaysia (UPM), 43400 UPM Serdang, Selangor, Malaysia, Malaysia. Email – ar_muhaimin@upm.edu.my

sustainable development (Enell *et al.*, 2016). The effective handling of wastewater and soil pollution will benefit not only the environment and the ecosystem, but also improve the quality of human life. That is why it is imperative to devise a suitable method to overcome contaminated soil and wastewater issues, with low cost and good operational efficiency.

One of the suitable, sustainable and green approaches to treat wastewater and contaminated soil is through phytoremediation. In the past few years, phytoremediation has gained interest for the management of contaminated sites, including chemical or heavy metal contaminants. Phytoremediation has been defined by Truu *et al.* (2015) as “technology that is based on the combined action of plants and their associated microbial communities to degrade, remove, transform, or immobilize the toxic compounds present in soils, sediments, and more recently in polluted groundwater and wastewater in treatment wetlands”. There are various types of contaminants that can be treated using phytoremediation, for instance pesticides, heavy metals, chlorinated solvents, petroleum hydrocarbons and radionuclides in soil and water. As compared to the conventional techniques of remediation, phytoremediation is low-cost, does not induce secondary contaminants, and presents low disruption towards the environment (Oh *et al.*, 2014; Truu *et al.*, 2015). However, the effectiveness of the treatment wetlands for phytoremediation depends on the efficiency of the phytoremediator plant itself. Therefore, it is very important to select the most suitable plants to effectively treat the different types of wastewater.

One of the potential phytoremediator plants to be considered is *Pennisetum purpureum*. *Pennisetum purpureum*, also known as *Cenchrus purpureus* (synonym), Napier grass, Uganda grass or elephant grass, is a monocotyledonous flowering plant that belongs to the Poaceae family of grasses. This grass is a native plant to subtropical Africa, from which it is believed to have been distributed to other tropical and subtropical regions around the world (Negawo *et al.*, 2017). There are a lot of *P. purpureum* cultivars. Over the last two decades, several *P. purpureum* cultivars have been introduced in Malaysia, for instance, King grass, Taiwan Napier, Red Napier and

Dwarf Napier (Halim *et al.*, 2013). More importantly, *P. purpureum* is well known to be used as an animal feed, mainly in the cut and carry feeding systems, or made into hay or silage (Orodho, 2006). In addition, *P. purpureum* has also been used to produce biofuels because of its high cellulose content (Takara and Khanal, 2015). This high cellulose content can be utilized as a carbon source for the production of biofuels, such as ethanol and butanol (Ko *et al.*, 2017; He *et al.*, 2017). Furthermore, *P. purpureum* has also been used to scavenge pollutants, thus making this plant a suitable candidate in phytoremediation strategies.

2. *Pennisetum purpureum* as a phytoremediator

2.1 Characteristics of *Pennisetum purpureum* as a phytoremediator

A good phytoremediator species should have fast growth rates and high levels of biomass to accumulate large amounts of the contaminants in their systems. Fast-growing plants will make an exceptional phytoremediator due to their extensive root system, rapid growth and high water uptake (Couselo *et al.*, 2012). *Pennisetum purpureum*, with its perennial nature, is well known as one of the fastest-growing plants in the world, and has high biomass yield (Karlsson and Vasil 1986; Cutts *et al.*, 2011). Besides, according to Cutts *et al.* (2011), *P. purpureum* also has an efficient photosynthetic rate. This is accomplished by the unique spatial and physical properties of the bundle sheath cell wall of the plant which allows for minimal CO₂ diffusion or leakage. As reported by Oliveira *et al.* (2014), *P. purpureum* generates up to 78 tons/ha of dry matter yield yearly, thus signifying its rapid growth.

Besides rapid growth, an ideal phytoremediator must also possess a high tolerance to the pollutants and the ability to degrade or concentrate high levels of pollutants in its biomass (Buhari *et al.*, 2016). As reported by Ishii *et al.* (2015), *P. purpureum* can withstand several highly contaminated conditions. Liu *et al.* (2009) and Kang *et al.* (2012) also demonstrated that *P. purpureum* is resistant to media that are contaminated with heavy metals, including soil with a high copper level in a pot trial and in solutions containing stable caesium. This thus

indicates that *P. purpureum* could be an ideal phytoremediator.

In addition, an ideal phytoremediator must also be tolerant to poor soil conditions. This is because, most of the contaminated soils are low in pH, have high salinity, highly compact structure, and have very low or high water content (Lekić *et al.*, 2017). In general, *P. purpureum* is an undemanding plant in terms of nutrient supply. It is capable of surviving on a broad range of soils; from poorly drained clay soils to excessively drained sandy soils, with the pH ranging from 4.5 to 8.2 (Rahman *et al.*, 2008). Next, *P. purpureum* can also grow in the presence of contaminants like lead or chromium, without requiring mineral and nutrient supplements. Islam *et al.* (2017) demonstrated that there was no significant difference in the biomass yield of the *P. purpureum* when grown in the normal loamy soil or sandy soil even though the soil constituents (*e.g.*, calcium, copper, phosphorus, magnesium, iron) were different. This further indicates that *P. purpureum* is robust enough to have similar growth rates either in polluted soil or in a normal, unpolluted one.

Moreover, a good phytoremediator should also be easy to handle and have a low maintenance cost (Lekić *et al.*, 2017). *P. purpureum* is easy to grow, and it grows best in high and well-distributed rainfall areas where the annual rainfall is more than 1,000 mm (Orodho, 2006). Nevertheless, *P. purpureum* is also well adapted to drought conditions (Anderson *et al.*, 2007). This is due to its deep root system which makes it possible to endure and stay alive during the drought (Kebede *et al.*, 2016). So, the water requirement of *P. purpureum* is not an issue. In a nutshell, this versatile and durable plant makes an ideal choice as a phytoremediator in a treatment wetland system for managing wastewater and contaminated soil (which will be further discussed in later section).

2.2 Types of phytoremediation

Phytoremediation systems can be divided into several categories based on their mechanisms of removal (Figure 1) which are phytoextraction, phytofiltration (rhizofiltration), phytostabilization, phytovolatilization, and phytodegradation (Etim, 2012). Table 1 shows the phytoremediation

processes involved when using *P. purpureum* as the phytoremediator.

Figure 1. Potential phytoremediation strategies by *P. purpureum*. The pollutants in the soil or water can be immobilized (phytostabilization) and translocated into roots (phytofiltration/rhizofiltration) through plasma membrane transporters. The pollutants can then be transported from the roots into the xylem and translocated into the shoots (phytoextraction). Phytovolatilization of the pollutants can be achieved through modification of these elements into volatile compounds. The degradation of organic pollutants into simple forms, which are considered non-polluting agents (phytodegradation) in the plant, can be achieved by enzymes (Dhankher *et al.*, 2012; Mosa *et al.*, 2016).

Table 1. The processes involved in phytoremediation by *P. purpureum* as a phytoremediator.

Process	Description	Type of waste	Contaminant	Final contaminant form	Reference
Phytoextraction (Hyper accumulation)	Uptake of contaminants into roots by accumulation or harvestable shoots	Cd-contaminated hydroponic solutions	Cadmium (Cd)	Phytochelatin (PC)–metal complex*	Ishii <i>et al.</i> (2015)
		Tannery sludge	Chromium (Cr), copper (Cu), zinc (Zn) and lead (Pb)		Juel <i>et al.</i> (2018)
			Mercury (Hg)		Abad <i>et al.</i> (2017)
		Mine tailing pond	Nickel (Ni)		Singh (2003)
		Nickel chloride salt solution	Caesium (Cs) Chromium (Cr), copper (Cu), manganese (Mn) zinc (Zn), and lead (Pb)		Kang <i>et al.</i> (2012) Ma <i>et al.</i> (2016)
Phytovolatilization (Volatilisation by leaves)	Volatilization of contaminant by leaves	Crude oil	Hydrocarbon	Hydrocarbon gasses	Ayotamuno <i>et al.</i> (2006)
		Se-laden saline drainage sediment	Selenium (Se)	Volatile DMDSe and DMSe	Kikuchi and Tanaka (2012)
Phytodegradation (Degradation in plant)	Microbial degradation in the rhizosphere stimulated by plants	Organic compound	POME final discharge	CO ₂ , H ₂ O, inorganic nutrient, simpler organic compound	Ujang <i>et al.</i> (2018)
Phytostabilization (Complexation)	Stabilization of contaminant by binding/complexation	Organic compound	Swine wastewater		Klomjek <i>et al.</i> (2016)
		Cadmium	Cadmium (Cd)-contaminated hydroponic solutions	Insoluble oxidation state**	Wiangkham and Prapagdee (2018)
Phytofiltration (Rhizosphere accumulation)	Removal of contaminant by plant roots	Chlorobenzenes	Sewage sludge	Metal cation**	Alvarenga <i>et al.</i> (2017)
		Tannery sludge	Chromium (Cr), copper (Cu), zinc (Zn) and lead (Pb)		Juel <i>et al.</i> (2018)

Source: *Yadav, (2010); **EPA, (2000)

2.2.1 Phytoextraction

Phytoextraction, also referred to as phytoabsorption, phytoaccumulation or phytosequestration, is a process of contaminant uptake through the plant roots, preferably heavy metals from the contaminated soil and water (Razzaq, 2017). The contaminants then accumulate in the shoots or aerial parts of the plant. This process is then continued by harvesting the plant biomass to ensure the contaminants are safely disposed of, or removed from the remediated area (Mahar *et al.*, 2016, Yadav *et al.*, 2018).

Phytoextraction by fast-growing, high biomass-producing *P. purpureum* has been recognized as a promising approach for the remediation of water and soil pollution. This is because *P. purpureum* has the mechanism to tolerate high heavy metal concentrations accumulated in its shoots. For example, from the study by Ishii *et al.* (2015), the cadmium concentration in the soil was reduced by about 4.6% and 2.6% in a single year of *P. purpureum* cultivation with twice and once cutting, respectively. In addition, cadmium concentration of 1.47 mg/kg, which is almost equivalent to 15 μ M cadmium, in the soil had no observable inhibition on the growth of *P. purpureum* (Ishii *et al.*, 2015). The plant growth was as healthy as in cadmium-free soils which demonstrated that *P. purpureum* is a potential cadmium phytoextractor. Moreover, results from the study by Ma *et al.* (2016) also suggests that *P. purpureum* has good phytoextraction potential in removing other heavy metals such as lead, manganese, zinc, copper, and chromium from contaminated tailing wastes. Basically, tailing wastes, also known as mine dump is the waste rock or other material that overlies on mineral body and is displaced during mining without being processed. This waste is heavily polluted with heavy metals; which could pose serious threats to human health and productivity in agriculture (Chileshe *et al.*, 2019).

There are several advantages of phytoextraction in remediating heavy metals in soil and wastewater. Firstly, the contaminants are permanently removed from the contaminated area. In some cases, the contaminants can also be recycled from the contaminated plant biomass (Etim, 2012), for example, recycling the metals from the biomass ash. Another benefit is the

inexpensive cost of phytoextraction as compared to conventional methods (Etim, 2012), for example, electrochemical deposition, ion exchange, adsorption, flotation and chemical precipitation (Gunatilake, 2015). Besides being expensive, the conventional methods of extraction also have significant disadvantages associated with incomplete removal of the metal contaminants, large energy consumptions, and toxic sludge production, as compared to using phytoremediation plants such as *P. purpureum* (Eccles, 1999; Barakat, 2011). Even though phytoextraction is effective in removing heavy metal-polluted wastewater and soil, the disadvantage of this method is that the plant biomass must be harvested and disposed of properly in compliance with the set standards by the governing body (Raskin and Ensley, 2000).

2.2.2 Phytovolatilization

Similar to phytoextraction, phytovolatilization refers to a process where the contaminants, primarily organic compounds, are being absorbed into the plant body from contaminated soil or wastewater. However, unlike phytoextraction, phytovolatilization subsequently transforms and volatilizes the absorbed compounds into the atmosphere through its leaves by transpiration (Yadav *et al.*, 2018), thus bypassing the need to harvest and dispose of the contaminated plant biomass as in phytoextraction. The absorption occurs as the plants absorb water and organic contaminants, with the contaminants being changed and reformed along the way as the water travels along the vascular system of the plants from the roots to the leaves. Then, the transformed compounds are volatilized into the air surrounding the plant (Akporkor and Muchie, 2010). For example, volatile organic compounds, such as mercury and trichloroethylene may be volatilized by either direct phytovolatilization which is volatilized from the stem and leaves in gaseous form, or by indirect phytovolatilization which is from the soil due to plant root activities (Limmer and Burken, 2016).

Phytovolatilization by *P. purpureum* involves the accumulation of the contaminants, the uptake of the heavy metals or organic compounds, and their subsequent conversion into gaseous species. This is achieved by partitioning of the absorbed

contaminants into air spaces within the plant with a subsequent release into the atmosphere. According to Kikuchi and Tanaka (2012), besides its ability to accumulate selenium, *P. purpureum* has been discovered to have a specific metabolic selenium pathway, which means that selenium can be released as a volatile compound to the atmosphere. As explained by Gupta and Gupta (2017), the mechanism of selenium volatilization begins with the selenium present in soil being carried inside the plant through sulphate transporters that are present in the plasma membrane of root cells. It is then assimilated into organic selenium *via* the sulphur metabolic pathway inside the plant and volatilized as dimethylselenide (DMSe) and dimethyldiselenide (DMDSe) into the atmosphere. The volatilization of selenium in the form of DMSe and DMDSe may help prevent the toxicity inside the plant (Gupta and Gupta, 2017). Moreover, according to Pilon-Smits (2015), selenium released from plants has a negative effect on selenium-sensitive ecological partners, which may defend the plants from pathogens and herbivores. Conversely, it could cause allelopathic effects on the neighbouring plants. Besides selenium, the other compounds that can be volatilized by *P. purpureum* are petroleum hydrocarbons as stated by Ayotamuno *et al.* (2006). The results of the total hydrocarbon content from the study showed that phytoextraction and phytovolatilization could achieve the removal of petroleum hydrocarbons by approximately 83%.

2.2.3 Phytodegradation

Most of the phytoremediation methods previously described primarily worked on removing heavy metals. It should be noted that contaminated soil and wastewater contain high amounts of organic pollutants as well. That is why phytodegradation or phytotransformation is an important mechanism performed by the phytoremediator plant. Phytodegradation is specifically for the removal of organic impurities because of the non-degradable properties of heavy metals (Yadav *et al.*, 2018). Basically, this method involves the use of enzymes for the degradation of organic pollutants in plants. For example, the enzymes used are nitroreductase (conversion of explosives and other nitrated

compounds), nitrilase (transformation of cyanated aromatic compounds), peroxidase (conversion of phenolic compounds), and dehalogenase (transformation of chlorinated compounds).

The phytodegradation ability of *P. purpureum* has been tested by Ujang *et al.* (2018) by determining the chemical oxygen demand (COD), ammonia degradation and colour removal of palm oil mill effluent (POME) final discharge using a constructed wetland system. The results obtained from this study showed that *P. purpureum* successfully reduced COD level by 71.57%, ammonia by 85.97% and colour intensity by 87.62%. Furthermore, this result is also supported by Klomjek *et al.* (2016) with 64% and 70% removal efficiency of biological oxygen demand (BOD) and total Kjeldahl nitrogen (TKN), respectively.

2.2.4 Phytostabilization

Phytostabilization, also referred to as phytoimmobilization, is the mechanism to reduce the bioavailability of pollutants, especially heavy metals in the environment by transforming the toxic compounds into non-toxic or less toxic forms and immobilizing them in the soil. For heavy metals present in a contaminated area, phytostabilization is not able to reduce their concentration, but instead, it prohibits their movement by accumulation through the roots, or precipitation within the rhizosphere in a similar manner to phytofiltration which operates under submerged conditions (Khalid *et al.*, 2017).

P. purpureum can be regarded as a phytoremediator plant for cadmium phytostabilization. In the study by Wiangkham and Prapagdee (2018), it was stated that after six months of *P. purpureum* transplantation, cadmium concentrations in the roots were higher than in the shoots by 7.78-fold. This may be due to the plant roots having a retention function of heavy metals, due to insolubilization or compartmentalization in cells, thereby avoiding their release to the xylem (Page and Feller, 2015). Thus, the heavy metals will be retained much more in the roots as compared to in the shoots. A longer retention time allows for more of the treatment processes to be completed. From this, it can be concluded that the plants that have

a high cadmium content in the roots and low cadmium content in the shoots are suitable to be used for cadmium phytostabilization. It is also worth noting that the roots of *P. purpureum* have a strong ability to retain cadmium. In addition, the roots containing a stabilized form of cadmium can be harvested, and the cadmium can be recovered from the ash after the ashing process (Sahoo *et al.*, 2016).

2.2.5 Phytofiltration

Phytofiltration is the method of phytoremediation that involves filtering and removing contaminants, mainly toxic substances, from wastewater. Limmer and Burken (2016) explained that phytofiltration functions by utilizing the plants' roots (rhizofiltration), seedlings (blastofiltration), or excised plant shoots (caulofiltration), to inhibit the organic pollutants from entering into streams or groundwater. Similar to phytoextraction, this method also involves the uptake of pollutants, especially heavy metals, from the roots and their accumulation in the plant biomass. This method also relies on the dense root system of the phytoremediator plant to slow down the flow of the wastewater just enough for sedimentation to occur. These movement reduction of the wastewater *via* a dense root mass is known as "hydraulic control". In conjunction, the slower speed of the water flow also gives ample time for the biota of the root system to react within the water. This results in the change of the surrounding pH because of the production of their metabolic product (Ratzke and Gore, 2018). The changes in pH then cause the precipitation of the heavy metals that will get trapped on the surfaces of the root of the plant (Ayangbenro and Babalola., 2017; Tangahu *et al.*, 2011). Both the uptake and precipitation of contaminants allow for cleaner water to be filtered out of the wetland system. As stated by Yadav *et al.* (2018), the ideal plant for phytofiltration should comprise several traits. These include the ability to generate a considerable amount of root biomass that can grow under submerged conditions, the ability to accumulate and tolerate significant amounts of heavy metals, as well as ease of handling. Fortunately, *P. purpureum* meets all the required criteria as the ideal plant for

phytofiltration as explained in subtopic 2.1 and 2.2.1.

P. purpureum has also been shown to be able to phytofiltrate contaminants like chlorobenzenes as stated by Alvarenga *et al.* (2017). Chlorobenzenes are aromatic organic compounds with low biodegradability and high toxicity (Nazari *et al.*, 2019). Soil or wastewater contaminated by these compounds is of great environmental concern (Alvarenga *et al.*, 2017). Chlorobenzenes are widely used in the production of electric transformers, lubricants, dyes and pesticides (Schroll *et al.*, 2004), which result in their dispersion to the environment. This problem can potentially be solved by planting *P. purpureum* in the contaminated area. Alvarenga *et al.* (2017) showed that by cultivating *P. purpureum* in sewage sludge for 150 days, the concentrations of 1,4-dichlorobenzene and 1,3,5-trichlorobenzene in sewage sludge decreased with a concomitant increase in the concentration in the roots along the cultivation period.

3. Applications of *Pennisetum purpureum*

The most common method in utilizing *P. purpureum* to remediate and manage wastewater and contaminated soil is by constructed wetlands. Constructed wetlands are an engineered system that has been designed to utilize the natural function of wetland vegetation, soil, and their microbial populations for the purpose of pollution control and waste management (Vymazal and Kröpfelová, 2008). The use of constructed wetlands for wastewater treatment has been increasing since the early 1980's (Carvalho *et al.*, 2017). This is due to the capability of constructed wetlands to improve the quality of wastewater either from domestic, industrial or agricultural sources.

The major components of a constructed wetland mainly consist of a container that contains water, a substrate, and the phytoremediator plants (Figure 2). Other than this, the microbial and aquatic invertebrates' communities, which are the other important components of wetland, will develop naturally (Mahmood *et al.*, 2013). The size of *P. purpureum* wetland system can be constructed either in a laboratory scale, pilot scale or large scale depending on their purpose and application. For

instance, Ujang *et al.* (2018) designed a pilot scale size (0.09 m^3) of horizontal flow constructed wetland for the treatment of palm oil mill effluent final discharge. The capacity of water loading for this design is about 5 L per day. In addition, for a large scale of wetland treatment system, the system can be constructed next to the wastewater effluent port as an *in situ* phytoremediation. The wastewater effluent can be channelled to the planted area undergoing the phytoremediation treatment, thus acting as an irrigation system.

Moving forward, one of the ideas to improve and upgrade this constructed wetland system is by constructing a mobile system. The constructed wetland system that consists of a container, substrates and phytoremediator plant can be set up on top of a vehicle as shown in Figure 3. The benefit of this mobile system is that it can become a support or back up system at the mill. In

addition, it is also feasible for a bioremediation of spillage, where the mobile wetland system can easily be transported to the spill area and the spillage can be immediately remediated.

Other than constructed wetlands, hydroponic systems can also be applied to treat wastewater. Hydroponically grown *P. purpureum* has been reported to produce a large biomass and accumulate high concentrations of caesium in the aerial parts (Kang *et al.*, 2012; Gupta and Walther, 2017). Besides, *P. purpureum* can also be applied *in situ* by directly transplanting it on the contaminated soil. For this method, the contaminated soil must be first ploughed before the transplantation of *P. purpureum*. The capability of this method was proven by a study of Ishii *et al.* (2015), where cadmium contaminated soil was successfully remediated with a reduction of 4.6%.

Figure 2. Constructed wetland design.

Figure 3. The new idea of mobile constructed wetland system. The polluted water can be pumped up from the polluted river, pond or any water system into the mobile constructed wetland through water pump (red arrow). The polluted water will then undergo phytoremediation and pass through the several layers of the constructed wetland. The clean water will then be discharged to the environment (blue arrow).

4. Management of *Pennisetum purpureum*

As previously discussed, *P. purpureum* has many qualities that make it an ideal phytoremediator: high biomass yield, fast growing rate, high tolerance to pollution, able to degrade contaminants, tolerant to poor soil conditions and having a low maintenance cost. However, this plant also has a few potential problems that might interfere in its role as a phytoremediator in a large scale phytoremediation.

One issue of *P. purpureum* is that it has been categorized as a potentially invasive species by the Florida Exotic Pest Plant Council and in the Global Compendium of Weeds (Randall, 2012). As reported by D'Antonio and Vitousek (1992), this grass is an aggressive invader with a fast growth rate which can easily colonize new areas and form dense growth. The problem arises when the invasion of this plant can change the structure and subsequently, the function of the natural ecosystem it invades (Gaertner *et al.*, 2014). For example, it can alter the hydrology cycles, fire regimes, nutrient cycles, biophysical dynamics, and community composition of the ecosystem it invades (D'Antonio and Vitousek, 1992). The invasiveness of *P. purpureum* was described by López *et al.* (2014), where the grass that was initially introduced as forage for cattle in the United States became a weed in sugarcane plantings and invasive in natural areas over time.

Since the containment issue of this plant needs to be heavily considered, methods for controlling and managing this grass must be first set before utilizing it as a phytoremediator to remediate polluted area.

Chemical control, for example, the use of herbicides, is the most effective method for controlling invasive species. As mentioned by Grey *et al.* (2015), herbicides, for example, sethoxydim, glyphosate, or imazapyr can potentially eliminate *P. purpureum* populations from affected areas. The results from their study disclosed that applications of imazapyr and glyphosate reduced *P. purpureum* population by 74 and 94% respectively, and reduced the plant stem height by 6 and 15%, respectively, as compared to the non-treated control. Although herbicides can be used to control this invasive grass, this routine will still pose potential negative impacts towards the environment due to the leaching of the herbicide components into the soil layer and underground water (El-Nahhal and Hamdona, 2017).

This invasive plant can also be controlled mechanically. This is achieved through physically removing the plant from the environment by cutting and pulling (Matrck, 2006). These procedures do not require any special licensing or introduction of any chemicals into the environment. In addition, this method of cutting and pulling will result in high production of

biomass, which can then be used as a source for bioenergy production.

5. Phytoremediation Coupling to Bioenergy production

Recently, the possible synergies between phytoremediation and bioenergy production have been increasingly investigated (Kumar *et al.*, 2017). Phytoremediation will remove harmful contaminants and improve soil quality and at the same time renewable bioenergy such as biogas could be produced by utilizing the biomass

harvested from the phytoremediation process (Hunce *et al.*, 2019). This is due to the fact that the robust growth of *P. purpureum* during phytoremediation of contaminated soil and wastewater also indicates an increasing supply of fermentable sugars needed for the increased and continued bioenergy production. This integrated approach can lead to a more sustainable, eco-friendly, and economical alternative to conventional energy resources (Kumar *et al.*, 2017). This is also one of the zero-waste concept management since all the biomass is being fully utilized (Figure 4).

Figure 4. The Phytoremediation-Bioenergy Coupling Zero-Waste Concept.

In this context, the efficiency of *P. purpureum* for bioenergy production cannot be denied as it has been well studied that it can serve as a feedstock for biofuel processing (Mohammed *et al.*, 2015; Mohammed *et al.*, 2019; Takara and Khanal, 2015). As mentioned previously, *P. purpureum* is fast growing, has high biomass yield, and also has impressive adaptability to the environment which makes it a stable renewable source to produce biofuel (Wen *et al.*, 2015). Besides, the structural analysis of *P. purpureum* shows that it has considerable cellulose, hemicellulose and lignin contents which are 40–50%, 20–40% and 10–

25% by weight respectively; which in turn indicate substantial sources of sugars for sustainable biofuel production (Mohammed *et al.*, 2015; Takara and Khanal, 2015).

There are various studies conducted on the production of ethanol from *P. purpureum*. Yasuda *et al.* (2014) reported that by performing fermentation process using low-moisture anhydrous ammonia-treated *P. purpureum*, about 74.1% ethanol yield was achieved. In addition, from the finding of Bensah *et al.* (2015), *P. purpureum* exhibited the highest ethanol yield at 65.1% when compared with other biomass types

studied (bamboo wood, rubber wood, Siam weed, and coconut husk). The ethanol yield's theoretical maximum is 35%. This demonstrated that this plant offers a promising resource for biofuel production.

Moreover, the potential use of recovered *P. purpureum* contaminated with heavy metals for ethanol production has been investigated by Ko *et al.* (2017). The study showed that the zinc-polluted biomass resulted in 10% less efficient enzymatic hydrolysis of substrate when compared with the unpolluted biomass. On the other hand, cadmium polluted biomass resulted in 33% less efficiency as compared to unpolluted biomass. Chromium showed similar results as cadmium. Furthermore, the fermentation efficiency of the heavy-metal-containing-biomass was also found to be higher than the control biomass. These findings thus conclude that ethanol production from biomass that was harvested after phytoremediation is feasible.

CONCLUSION

Even though rapid industrialization and urbanization signify major economic growth that boosts a country's gross domestic product, it also causes tremendous stress on the environment and the surrounding ecological system (Li *et al.*, 2019). The production of wastewater and contaminated soil as the by-product of this economic development, if left untreated, will leave permanent adverse effects on the environment and its inhabitants (Wen *et al.*, 2017). That is why phytoremediation technologies, which include phytostabilization, phytodegradation, phytovolatilization and phytoextraction, are the most promising strategies to remedy this problem. Using *P. purpureum* that is proven to be an efficient phytoremediator in a wetland system will make phytoremediation more sustainable and more practical in treating wastewater and soil pollution. In addition, *P. purpureum* which produces high biomass yield has also been used to produce bioenergy (Takara and Khanal, 2015). Hence, this phytoremediation approach could also benefit from the income generated through the production of bioenergy, both for its own maintenance as well as generating extra profit.

Thus, phytoremediation not only makes the environment cleaner, but also contributes to the growth of the economy; thereby providing a win-win solution for all. However, deeper research and pilot studies still need to be conducted to help improve and implement this phytoremediation technology together with bioenergy generation.

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