Towards Resilient Futures

Can fibre-rich plants serve the joint role of remediation of degraded mine land and fuelling of a multi-product value chain?

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Abstract

Due to the many challenges associated with mine closure and management practices during a mine's lifetime that make insufficient provision for "during mining" practices with respect to environmental sustainability and progressive closure approaches, there are large areas of degraded mine land, poorly rehabilitated operations and abandoned mines across South Africa, resulting in severe environmental degradation and complex socio-economic issues. To aggravate this, the dropping numbers of jobs in mining and minerals processing and the many mines approaching ore reserve end-of-life are having a substantial impact on the health of the economies of mining regions. One approach to mitigate these impacts is to seek to transform the large areas of degraded or unused mine land into a sustainable post-mining landscape to support surrounding communities. Fibre crops have the potential to remediate polluted soil through their ability to bioaccumulate heavy metals in their biomass. At the same time, they can provide raw materials to support the manufacture of a vast array of products. In this 'community of practice' project, we explore the potential to develop economic complexity in mining and post-mining regions through value creation from fibre crops, while remediating the lands, leading to a vibrant and self-sufficient post-mining community.

In this first working paper, we investigate the ability of fibre crops to grow on mine land which is typically degraded to assist in the rehabilitation of this degraded land, whilst providing a range of raw materials, including fibre crops, for valorisation. This includes transformation of these fibre-based feedstocks into fibre-derived products as economic outputs. Soil and climate data from mining areas in South Africa were compiled and used to identify fibre crops for cultivation. The following crops were selected, based primarily on their temperature tolerance and rainfall requirement: *Bambusa balcooa*, flax, hemp, kenaf and sisal. While these crops can demonstrate the dual ability of remediating land and producing fibre, the efficacy of this dual system is challenged depending on the level of contamination of the degraded land. Fibre crops can usually tolerate low to moderately polluted soil, but a high level of pollution is detrimental to their growth, with the added risk of metal accumulation in the fibrous biomass, thus increasing the complexity of the processing of these raw materials into products of choice owing to the need to ensure product safety depending on the target markets. To maximise the crops' growth and fibre production on heavily contaminated land, it is recommended that the land is first restored by physico-chemical or biological means to provide a conducive environment for the fibre crops. It is further recommended that this feasibility study be extended to conduct field experiments on selected sites to further assess the potential and practicality of the proposed approach, while developing a refined inventory of its outputs and challenges.

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Abbreviations

ARC:	Agricultural Research Council
CDB:	cannabidiol
DST:	Department of Science and Technology
NRF:	National Research Foundation
PGMs:	platinum metal groups
SARChi:	South African Research Chairs Initiative
THC:	tetrahydrocannabinol

Glossary

Autochthonic species:	indigenous species
Cash crop:	a crop which is produced for its commercial value
Cultivar	a plant variety that has been produced in cultivation by selective breeding
Microbiome:	the microorganisms in a particular environment
Phytoremediation:	a process that uses various types of plants to remove, transfer, stabilise, and/or destroy contaminants in the soil and groundwater
Remediation:	the action of remedying something, in particular reversing or stopping environmental damage

1 Background to Study

1.1 The need for post-mine interventions

Since the late 1980s, with depleting mineral ore deposits and associated increased costs of mining, the advent of new mining regulations, increasing demands from labour, amongst others, nearly 6000 mines have terminated operation and been abandoned in South Africa, with full closure to meet legal specifications a rare event. Ineffective co-operation between mining companies, government, unions and related stakeholders lead to the unsuccessful or non-compliant closure of mines, creating a multi-faceted wicked problem. These mine closures in South Africa have resulted in numerous job losses (nearly 50, 000 from 2012 to 2015) and significant environmental impact on land, air and water quality, impact on quality of life and loss of biodiversity across the country (Mathews, 2017). Thus, people whose livelihoods depend on mining activities are severely impacted. Acid mine drainage, contamination by uranium and other metals, land degradation and deforestation are persistent in areas surrounding mining sites. Mining companies are being increasingly pressured to restore the landscape of degraded mine land post-mining to reduce the environmental and social liability left behind and open potential for the redevelopment of the area. However, incentives to actively support mining communities whose social and economic activities are severely affected post-mining are few. There is a need to find an innovative post-mining economy through reimagining routes to stable livelihood generation by addressing both environmental and socio-economic concerns associated with mine closure (Verster *et al.*, 2018).

Mining remains essential for delivery of the 'green' or low carbon economy. It plays an ongoing key role in South Africa's economy and remains essential for the development of South Africa. However, there is an increasing awareness that the sustainable development of these finite mineral resources must be coupled with the development of their regional locations such that a sustainable economic, environmental and social basis, independent of mining, is delivered by the collaboration of local and national government, the mining houses and the community during the 'life of mine', thereby avoiding degraded mining environments and economic devastation. Further to this, the issue of existing abandoned and degraded mine land needs addressing on socio-economic and environmental grounds.

The Resilient Futures Community of Practice project was conceptualised at the University of Cape Town by four SARChI chairs and funded by DST and NRF[1]. This project seeks to combine rehabilitation and the creation of a new economy which can sustain the mining region and community dependent on mining, post the life of mine. In active mining regions, we seek to develop this post-mining

[1] http://www.resilientfutures.uct.ac.za/about-Towards-Resilient-Futures

economic complexity during the life of mine through ongoing investment in the region, while abandoned mines can be treated retrospectively, but will require outside investment. In particular, this interdisciplinary endeavour proposes an innovative post-mining economy with the use of fibre crops to remediate degraded land and produce a renewable feedstock for valuable fibre-derived products, by investigating the bioprocessing, environmental, manufacturing, legal and economic aspects of the research. This report specifically focuses on the biomass, bioprocess and environmental aspects of the research to investigate the opportunities and challenges of using fibre crops as a vehicle for transforming degraded mine land while providing a renewable raw material for valorisation to fibre-based products and associated by-products.

1.2 Issues around degraded land and unsuccessful mine closure

The inefficacy of post-mining practices is reflected in the increasing number of abandoned mines in South Africa. A mine is only deemed closed if a closure certificate has been issued in terms of section 43 of the Mineral and Petroleum Resources Development Act (MPRD), 2002 (Section 43). Up until closure, the owner of the mine is responsible for any related liabilities linked to the mine and is further expected to financially support the minimisation of these liabilities within a legal framework (Sections 41 and 43). Section 46 of the act states that a mine is classified as derelict and ownerless (abandoned) in the absence of a closure certificate and no record of the owner. As from mid-2008, a report by the Council for Geoscience (CGS) to the DME identified 5906 abandoned mines, most of which were closed down before 2002 and thus before the MPRD Act (Mineral and Petroleum Resources Development Amendment Act, 2008; Department of Minerals and Energy, 2009).

The necessary level of engagement and incentivisation required for mining companies, working with stakeholders, regional and national governments, to seek out appropriate post-mining practices to transition from a mining landscape to a post-mining one is not yet embedded internationally or in South Africa. This must ideally happen during the life-of-mine (Harrison *et al.*, 2018) using the framework of an active economy to build the successor economy. The collection presented in “Green Mining: Beyond the Myth” compiled by Digby *et al.* (2018) explores many aspects of the required transformation from active mines, as reserves deplete, to active post-mining economies and communities, using approaches mindful of natural resources and the local social fabric. Factors to consider when securing adequate post-mining practice include characteristics of the areas, stable local communities, alternative resources, expert opinions, development opportunities for local authorities and communities, legal framework and environmental status and restrictions (Heikkinen *et al.*, 2008; Kuter, 2013; Slingerland and Wilson, 2015; Palogos *et al.*, 2017), further explored in Section 1.3.

1.3 Challenges of post-mining practices

In achieving post-mining economic succession, both the rehabilitation or restoration of the site as well as post-mining economic activities must be established. To set appropriate goals for any kind of post-mining transformation, the appropriate land use must be identified. The most common post-mining land uses are for agriculture, forestry, recreation, construction, conservation and artificial lakes (McHaina, 2001; Soltanmohammadi *et al.*,2010). An innovative type of land use is mining heritage tourism where historic mining sites with a strong history are used to attract tourists, facilitated by public sector, non-profit organisations and volunteers (Wirth *et al.,* 2012; Lane *et al.*, 2013). Kivinen *et al.* (2017) did a review on sustainable post-mining land use by examining the landscape characteristics in 51 metal mining sites which closed between 1924 and 2016 in Finland. The authors concluded that there was no universal scheme for sustainable post-mining land use and each mine had its own potential and limitations which influence the choice of post-mining land use. Many of the aforementioned post-mining land uses are applicable in both developed and developing countries where mining occurs in remote areas and away from settled communities (Limpitlaw and Briel, 2014). Where no post mining land use has been established, these areas turn to wilderness areas and the primary concern is to avoid environmental impact, with little expectation of replacing the economy of the mine with an alternative economy.

Where mining activities are close to human settlements, insufficiently planned post-mining land use can result in unsustainable land uses such as informal settlements such as the East Rand and West Rand, Gauteng (Limpitlaw and Briel, 2014). In those areas, post-mining land use requires a strong anthropogenic focus. This must both ensure non-exposure of the settlements to environmental risk and, importantly, must consider the post-mining economy (Slingerland and Wilson, 2015). Following identification of adequate post-mining land use, the transformation of the degraded mine land to this use is required, typically using a selection of remediation, rehabilitation, reclamation and restoration approaches, depending on the goal. Lima *et al.* (2016) highlighted that these terms are not interchangeable as they address different end goals.

Remediation is mostly focused on 'cleaning up' the contaminated soil using mostly chemical and physical techniques such as pneumatic fracturing, solidification/stabilisation, vitrification, excavation/removal of contaminated soil layer, chemical oxidation, soil washing, chemical precipitation, ion-exchange, adsorption, membrane filtration and electrochemical technologies; more details can be found in Bhargava *et al.* (2012), Bharti & Kumar Banerjee (2012) and Mahar *et al.* (2016). The main issue about conventional remediation techniques is their focus on expensive *ex situ* decontamination with lack of consideration for resulting ecological impacts (McGrath *et al.,* 2001).

Restoration takes on an ecological approach, seeking to salvage and re-establish pre-mining ecosystems. In the cases of heavily contaminated land and regions in which the anthropogenic activities have changed substantially, restoration can be too ambitious, with reclamation more feasible, as it seeks an alternate ecosystem better suited to the current activities of the region which can function in a similar fashion to the pre-existing ecosystem (Foley *et al.*, 2005; Powter *et al.*, 2012). Rehabilitation, on the other hand, centres on the sustainable management of the land by identifying the correct post-mining land use (Wali, 1996; Haigh, 2007).

Restoration and reclamation techniques take on a more biological approach by facilitating the establishment of functional ecosystems which seek to decrease the pollution load of the degraded mine land. One technique which has been gaining a lot of attention is phytoremediation, which uses plants to remediate and clean up the contaminated land. While it is termed as a remediation technique, according to the definitions set out by Lima *et al.* (2016), phytoremediation may fulfil the restoration and, particularly, reclamation objectives and is further discussed in Section 2.1. This method is usually cheaper and more sustainable than conventional ex situ remediation techniques, with the added possibility of rendering degraded mine land more amended to agriculture (Jiang *et al.*, 2015).

Increasingly, we must differentiate between remote mining environments which require an environmental or ecological solution alone and those set within stable settlements that also require facilitation of post-mining economic succession.

1.4 Proposing a sustainable post-mining landscape for South Africa: the case of fibrous plants

The requirements of post-mining practices in South Africa are complex in nature and multi-faceted, with the simultaneous need to remediate degraded mine land and to create new economic activities to provide meaningful work for the surrounding communities whose livelihoods previously depended on mining activities. To achieve this, degraded mine land must be considered a substantial resource to be transformed into a reusable form of land with potential to sustain production of a renewable feedstock or raw material for valorisation into the follow-on economic mix. Conventional remediation techniques are often uneconomical and often offer no real solution in re-establishing a regenerative and stable ecosystem.

In addressing the long-term sustainable post-mining arena in the African, and particularly South African, context in which operating mines are typically co-located with human settlements, the needs for both restoration or reclamation of the degraded environment and for establishment of the post-mining economy must be addressed concomitantly. The availability of land and importance of job creation highlight the potential for the generation of a renewable feedstock or raw material through cropping. The varying levels of metal contamination of the land highlight both the need to remediate the land and the potential for value generation from the metal. Increasingly, ex situ remediation approaches are losing favour, owing to both expense and their complete degradation of the ecosystem present, while the use of in situ biological remediation such as phytoremediation is gaining traction.

Here we explore the opportunity to intercalate land remediation or reclamation with the generation of a renewable raw material stream to sustain a new, post-mine complex economy with a diverse product range. For this, we target the production of fibre crops, motivated in Section 3, with potential to sustain a range of processes to high(er) value fibre-based products (Section 3.2) expanded on in Working Paper 2 (Broadhurst *et al.,* 2019). We acknowledge the potential for further products, including specialty products and bioenergy, from the non-fibrous components of this crop. We address the potential of the fibre crops to contribute to either phytoremediation for metal removal or phytomining for metal recovery or both, relative to the need to use hyperaccumulators for phytomining, motivated in Section 3.3 and 3.4. Further, we acknowledge the progressive nature of the land reclamation with ongoing cycles of plant cultivation. If successful, this approach can achieve the dual role of land reclamation and development of a sustainable value chain with economic benefits further explored in Working Paper 3 (Allen *et al.*, 2019).

2 Exploring Phytoremediation for Remediation and Reclamation

2.1 Phytoremediation and phytomining explained

The concept of phytoremediation was first introduced in the 1970s as the use of plants to extract, sequester and detoxify environmental contaminants such as heavy metals, radionuclides, pesticides and polychlorinated biphenyls from the soil (Ali *et al.*, 2017). An overview of the different type of phytoremediation techniques is presented in Table 2-1.

Table 2-1: Overview of phytoremediation techniques adapted from Ali *et al. (2017)*

Techniques	Description	References
Phytoextraction (Phytoaccumulation)	Accumulation of pollutants in harvestable biomass i.e. shoots	Erdei *et al.* (2005)
Phytofiltration	Sequestration of pollutants from contaminated waters by plants	Tangahu *et al.* (2011)
Phytostabilisation	Limiting the mobility and bioavailability of pollutants in soil by plant roots	Tangahu *et al.* (2011)
Phytovolatilisation	Conversion of pollutants to volatile form and their subsequent release to the atmosphere	Erdei *et al.* (2005)
Phytodegradation	Degradation of organic xenobiotics by plant enzymes within plant tissues	Pulford and Watson (2003)
Rhizodegradation (Phytotransformation)	Degradation of organic xenobiotics in the rhizosphere by rhizospheric microogranisms	Mahar *et al.* (2016)
Phytodesalination	Removal of excess salts from saline soils by halophytes	Ali *et al.* (2013)

The two most common techniques used in the rehabilitation of degraded land are phytostabilisation and phytoextraction. Phytostabilisation decreases the soil metal bioavailability using both plants and soil amendments. Phytoextraction uses plants to extract metals by concentrating the metals in the harvestable parts of the plants (Salt *et al.*, 1998; Vangronsveld and Cunningham, 1998). The work of van der Ent (2013) has demonstrated the targeted accumulation of specific metals to specific regions of the plant, assisting in both metal concentration and selective recovery. Phytoextraction usually consists of the following steps (Vassilev *et al.*, 2004):

(i) Cultivation of the appropriate plant/crop species on the contaminated site.

(ii) Removal of harvestable metal-enriched biomass from the site.

(iii) Postharvest treatments (e.g. composting, compacting, thermal treatments) to safely dispose of hazardous waste or to recover the metals which may have an economic value.

The recovery of metals which have monetary value via phytoextraction is typically termed phytomining (Brooks *et al.*, 1998; McGrath and Zhao, 2003).

One of the main advantages of phytoextraction is the lower associated costs when compared to the traditional remediation methods mentioned in Section 1.2. In fact, using values from Glass (2000) and Rock *et al.* (2000), phytoextraction is on average ten times less costly than landfill excavation. It also has less impact on the associated ecosystems of the area. Additionally, phytomining offers the possibility of reclaiming significant amounts of metals embedded in the soils. This has typically been done from the ash of the plants without the need to pay for safe disposal (Chaney *et al.*, 1997). There exist two main approaches for phytoextraction; namely, continuous or natural phytoextraction and induced or chemically assisted phytoextraction. Natural phytoextraction relies on the plants' ability to uptake metals while assisted phytoextraction requires the use of chelating agents, which increase metals' solubility and facilitate their uptake by the plants (Ali *et al.*, 2017).

2.2 Suitability of plants for phytoextraction of heavy metals

The earliest concept of phytoextraction stemmed from a type of plant termed metal hyperaccumulators which have the ability to uptake and tolerate significantly higher levels of metals than non-accumulator plants (Brooks *et al.*, 1977; Revees and Baker, 2000). To be classified as a hyperaccumulator, a plant must have potential to accumulate in their dry weight foliar tissue one of the following concentrations: > 100 µg/g cadmium, thallium, or selenium; > 300 µg/g of cobalt, copper or chromium; > 1000 µg/g of nickel, arsenic, lead or rare earth elements (REEs); > 3000 µg/g of zinc, or > 10 000µg/g of manganese (Baker and Brooks, 1989; Reeves, 2003; van der Ent *et al.*, 2013). A list of the most common hyperaccumulators is shown in Table 2-2.

Over recent years, research has extended to consider plants other than hyperaccumulators for phytoextraction, since phytoextraction can be more economically feasible if the crops used produce biomass with an added value (for example: energy crops, fibrous plants and fragrance-producing crops) (Schwitzguébel *et al.*, 2002; Pandey *et al.*, 2016). Bhargava *et al.* (2012), Ali *et al.* (2013) and Mahar *et al.* (2016) identified the following desired characteristics to consider in identifying plants suitable for phytoextraction:

- Massive growth potential and high biomass production
- Extensive root system and root developing capacity under adverse conditions
- Ability to grow outside their usual area of collection
- Higher accumulation rate of target metals from soil and translocation of the accumulated metals from roots to shoots for successful phytomining
- Tolerance to the toxic effects of the target heavy metals

- Good adaption to prevailing environmental and climatic conditions (drought, temperature, humidity, salinity, nutrient deficiency and waterlogging)
- Easy cultivation, harvest and resistance to attack by pathogens and pests
- Repulsion to herbivores to avoid food chain contamination

Therefore, there are two ways that phytoremediation can take place: either by using natural hyperaccumulators which possess little economic value but concentrate the metals to higher levels or by using high biomass-producing non-hyperaccumulators which concentrate the metals to a lesser degree into different parts of the plant and provide biomass of high economic potential. Table 2-3 summarises the advantages and disadvantages of these two types of phytoremediation or phytomining. The main advantage of using natural hyperaccumulators is their high metal bioaccumulation potential, often limited to one specific metal and hence well-suited for phytomining for economic recovery of the specific metal. Non-hyperaccumulators exhibit less metal specificity, but they are not naturally inclined to bioaccumulate metals as efficiently as hyperaccumulators.

Table 2-2: List of common hyperaccumulators

Element	Threshold (µg/g)	Species demonstrating the highest concentration	References
Arsenic (As)	> 1000	*Pteris vittata*	Ma *et al.,* (2001)
Cadmium (Cd)	> 100	*Arabidopsis halleri*	Stein *et al.,* (2017)
Copper (Cu)	> 300	*Aeolanthus biformifolius*	Malaisse *et al.,* (1978)
Cobalt (Co)	> 300	*Haumaniastrum robertii*	Brooks *et al.,* (1977)
Manganese (Mn)	> 10 000	*Virotia neurophylla*	Jaffre *et al.,* (1979)
Nickel (Ni)	> 1000	*Berkheya coddii*	Mesjasz-Przybyłowicz *et al.,* (2004)
Lead (Pb)	> 1000	*Noccaea rotondifolia subsp. cepaeifolia*	Reeves and Brooks (1983)
Rare earth elements (lanthanum, La; cerium, Ce)	> 1000	*Dicranopteris linearis*	Shan *et al.* (2003)
Selenium (Se)	> 100	*Astragalus bisulcatus*	Galeas *et al.,* (2007)
Thallium (Tl)	> 100	*Biscutella laevigata*	LaCoste *et al.,* (1999)
Zinc (Zn)	> 3000	*Noccaea caerulescens*	Reeves *et al.,* (2001)

Table 2-3: Advantages and disadvantages of heavy metals phytoextraction using natural hyperaccumulators or high biomass producing non-hyperaccumulators (Suman *et al.*, 2018)

	Natural hyperaccumulators	High biomass producing non-hyperaccumulators
Advantages	- High bioaccumulation rates - Often autochthonic species which prevent the introduction of non-native and potentially invasive species	- High biomass production rate, possibility of production of biomass with added value - Low growth requirements - Possible use in short-rotation plantation - Number of species convenient for diverse range of climatic conditions, water regime, soil type, character of contamination - Often autochthonic species which prevent the introduction of non-native and potentially invasive species - Usually low metal/toxicant specificity – applicability for mixed contamination (both multiple heavy metals and mixture of heavy metals)
Disadvantages	- High metal specificity (often only single heavy metal element hyperaccumulated) - Often slowly growing, low-biomass producing species with specific ecology and requirements in terms of climate, soil characteristics, water regime etc.	- Low bioaccumulation rates – lengthy phytoextraction process

2.3 Limitations and economics of phytoextraction

While phytoextraction costs are significantly lower than conventional remediation techniques, its process is much longer and can take multiple years to remediate the soil adequately. Degraded mine lands also present substantial challenges for the successful establishment of plant communities, especially non-hyperaccumulators. The pH is usually too extreme, and the soil lacks nutrients and organic matter, typically aggravated by their low/high pH limiting bioavailability of nutrients. Some mining areas also suffer from water scarcity. To improve soil quality, the addition of organic residues such as compost or manure is recommended as well as the incorporation of viable native microbial communities or replacement microbial communities delivering the equivalent functionality to promote plant growth (Pandey and Singh, 2011; Pandey *et al.*, 2015). The appropriate end goal of any kind of post-mining transformation is required in order to make an informed decision on the choice of plants to be used. If the end goal is purely decontamination, hyperaccumulators are typically better suited to achieve this in a more targeted and rapid way. However, if the goal is to use the degraded land in a productive way, non-hyperaccumulators are likely to offer a greater range of economic outputs, enhancing the resilience of the post-mining environment created.

3 Exploring Fibre Crops for Renewable Raw Materials

3.1 Identifying fibre crops and their properties

Fibre crops can be classified on their type of fibres. There are six main classes of fibres; namely bast or stem fibres, leaf fibres, seed fibres, stalk fibres, grass fibres and wood fibres, as depicted in Figure 3-1. A list of the most commonly grown fibre crops in South Africa is shown in Table 3-1.

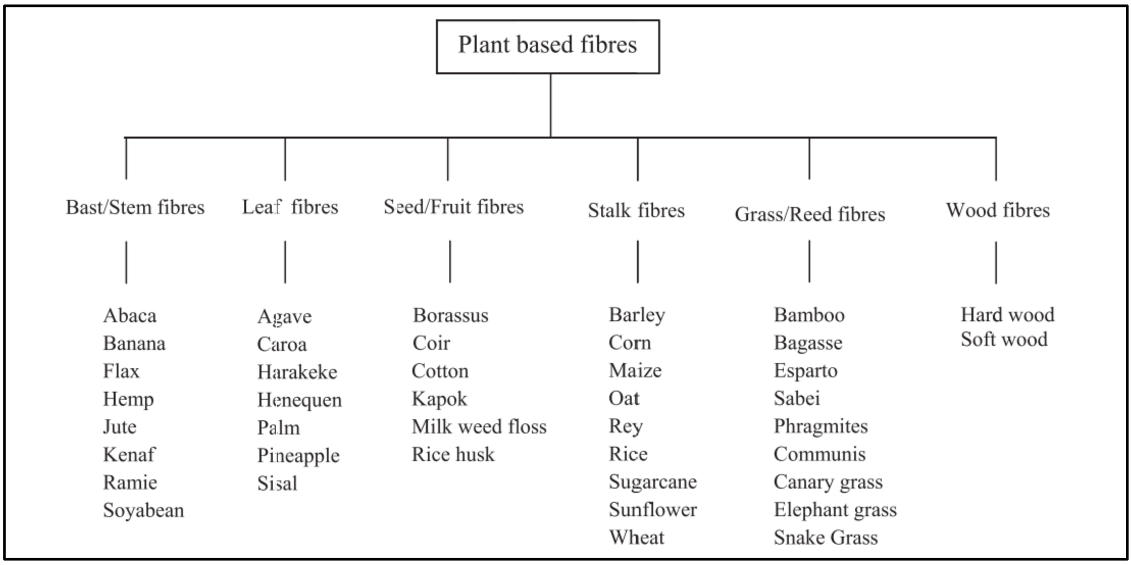

Figure 3-1: Classification of plant fibres (Ramesh et al., 2017)

3.2 Multi-product potential of fibre plants

Fibrous plants are versatile plants which can deliver multiple products from their fibres, seeds, or both, as expanded upon in Working Paper 2 (Broadhurst *et al.,* 2019). Natural fibres are becoming more and more attractive owing to them being renewable, cheap and biodegradable as compared to glass, carbon, plastic and other synthetic fibres (Vimal *et al.*, 2015; Ramesh *et al.,* 2016). Additionally, plant based fibres are increasingly being sought in the making of biodegradable resins to produce biocomposites which can be safely discarded at the end of their lifetime (Ramanujan *et al.*, 2002; Pérez *et al.*, 2011; Moothoo *et al.*, 2014). Fibres from a number of plants (e.g. flax, cotton, hemp, ramie, sisal, kenaf, jute, palm and so on) have also been reported to act as the reinforcing element in both thermoplastic and thermoset based composites (Ramesh *et al.,* 2017) The multi-product potential of fibres is demonstrated by the large number of products that can be manufactured from them, as seen in Table 3-2.

Table 3-1: Overview of the most commonly grown fibrous plants in South Africa adapted from Ecocrop (2007f), Bauholz (2018), Textile School (2019)

Name	Preferred soil type	Preferred annual rainfall (mm/yr)	Temp. tolerance (° C)	pH tolerance	Annual/perennial
Bamboo, *Bambusa balcooa*[2]	Clay, loamy	700 - 4500	9 – 35	4.5 – 7.5	Perennial
Bamboo, *Dendrocalamus asper*[2]	Rich	1200 – 1500	15 - 34	4.5 - 7	Perennial
Baobab, *Andasonia digitata*	Clay, sandy	250 – 4200	14 – 42	4.3 – 7.5	Perennial
Coconut, *Cocos nucifera*	Coarse sand, clay	1500 - 2500	13 – 35	5.5 - 7	Perennial
Cotton, *Gossypium hirsutum*	Sandy loam	450 – 1500	15 – 42	5 – 9.5	Annual
Flax, *Linum usitatissimum*	Loamy	450 - 750	5 - 30	5 - 7	Annual
Hemp, *Cannabis sativa*	Clay, silt loam	500 -700	6 - 32	6 – 6.5	Annual
Jute, *Corchorus capsularis*	Silt, sandy loamy, clay	1000 - 2500	13 - 45	4.8 – 5.8	Annual
Kapok, *Ceiba pentandra*	Loamy soil	750 - 3000	12 - 40	5 – 6.5	Perennial
Kenaf, *Hibiscus cannabinus*	All soil types	240 - 490	10 – 35	4.3 – 8.2	Annual
Palm, *Phoenix dactylifera*	Sandy soil	100 - 400	15 – 52	6 – 8.5	Perennial
Pinewood, *Pinus pinaster*	Sandy soil	850 – 950	> 13	5 - 6	Perennial
Sisal, *Agave sisalana*	All except clay	500 - 1500	10 – 32	4 - 6	Perennial

[2] The two bamboo species most suited for South Africa are *Dendrocalamus Asper* and *Bambusa balcooa,* since they are non-invasive and will not spread more than 1.5 metres (The Biomass Corporation, 2008)

Table 3-2: Multi-product potential of fibre plants adapted from Pari and Alexopoulou (2013)

	Primary products	Secondary products	Future products
Fibre-based products	- Chemical or mechanical pulp - Specialty paper - Textile (natural and regenerated) - Garments, bedlinen	- Bedding material - Shives - Seeds - Specific textiles	- Regenerated cellulose - Nanofibres - Moldable webs - Foam-formed structures - Functional textiles
Chemical products	- Sugars - Extractives (tall oil) - Oil (food and feed) - Pulp	- Lignin - Press cake - Cosmetics - Agro fine chemicals	- Sugar acids -Aromatic composites - Pharmaceuticals - Agro-chemicals
Composite products	- Reinforcement fibres - Particle and fibre board - Fibre reinforced/filled polyolefin composites (mostly for automotive industry)	- Bark - Minor composite products for everyday use	- Composite foams - Biocomposites -Foam-formed structures - 100 % biodegradable fibre reinforced composites, structural biocomposites
Energy products	- Black liquor - Biogas - Pellets - Shive briquettes and pellets	- Lignin - Bark	- Fatty acids - Bioethanol - 2nd generation biofuel (from high energy biomass

3.3 Fibre crops for phytoremediation

There are several physiological and biochemical factors which influence the hyper-accumulatory potential of a plant (Girdhar *et al.*, 2014). Fibrous plants which are mostly studied for phytoremediation are the bast fibre crops and the grass fibre crops due to their ability to produce high biomass (Bauddh *et al.,* 2017). Ludvíková and Griga (2019) proposed the following list of suitable fibre crops, for phytoextraction: cotton (*Gossypium hirsutm*), hemp (*Cannabis sativa*), silver grass (*Miscanthus)*, kenaf (*Hibiscus cannabinus*), ramie (*Boehmeria nivea*), reed (*Phragmites australis*) and flax (*linum usitatissimum*). Table 3-3 presents a list of fibre crops which shows phytoremediation potential and the metals which they usually target. In Table 3-4, typical accumulation concentrations and the typical zone of collection of these metals is given for a subset of these.

Table 3-3: Common fibre crops investigated for phytoremediation

Fibre crops	Targeted metals for phytoremediation	Study
Hemp	Cd, Zn, Fe, Cu, Ni, Pb	(Linger *et al.*, 2002; Arru *et al.*, 2004; Angelova *et al.*, 2004; Meers *et al.*, 2005; Mihoc *et al.*, 2012)
Kenaf	Cd, Zn, As, Fe, Pb, Cr	(Bada and Raji, 2010; Meera and Agamuthu, 2012; Arbaoui *et al.*, 2013, 2014; Bada, 2016)
Cotton	Pb, Cu, Zn, Cd	(Angelova *et al.*, 2004)
Cotton	As, Cr, Cu, Mn, Sr and Zn	(Kaur *et al.*, 2018)
Flax	Pb, Cd, Zn	(Hosman *et al.*, 2017)
Jute	Cd, Ni, Pb, As, Cr, Zn	(Uddin Nizam *et al.*, 2016)
Ramie	Cd, Pb, Zn	(Peng *et al.*, 2010)
Sisal	Cu, Pb, Cr, Zn	(dos Santos *et al.*, 2011; Mganga *et al.*, 2011)
Bamboo	Cu, Zn, Pb, Cd	(Babatunde *et al.*, 2002; Orina *et al.*, 2009)
Miscanthus sp.	As	(Hartley *et al.*, 2009)
Vetiver zizanioides	Pb/Zn mine tailings, Pb, Cd, Zn and Pb	(Shu *et al.*, 2002; Chen *et al.*, 2004)

Cd: Cadmium; Zn: Zinc; Fe: Iron; Cu: Copper; Ni: Nickel; Pb: Lead; As: Arsenic; Cr: Chromium; Mn: Manganese; Sr: Strontium

Table 3-4: Nature of accumulation in key fibre crops adapted from Angelova et al. (2004), Orina et al. (2009), dos Santos et al. (2011), Ahmed et al. (2015) and Ahmad et al. (2016)

Plant species	Metal bioaccumulation site	Metal selectivity	Metal uptake concentration
Bamboo[3]	Roots, shoots	Pb, Zn, Cr, Fe	Pb 36; Zn 43 (mg/kg of biomass)
Flax	Roots, capsule	Pb, Cd, Zn	Pb 311; Cd 13.1; Zn 490 (mg/kg soil)
Hemp	Roots, shoots, leaves and seed capsule	Ni, Pb, Cd, Zn, Cu	Ni 123; Cd 151; Cu 1530 (mg/kg leaves)
Kenaf	Roots, shoots, leaves and seed capsule	Pb, Cd, Zn	Pb 42.2 (mg/kg soil)
Sisal	Leaves	Cd, Zn, Cu	Cd 1850; Cu 1340 (mg/kg sisal fibre)

[3] Investigated bamboo species were water bamboo, giant bamboo (*Dendrocalamus gingateus*), yellow and green bamboo (*Bambusa spp*) (Orina *et al.*, 2009)

3.4 Fibre crops for the transformation of degraded mine land

Section 2 presented an overview of phytoremediation, more specifically the phytoextraction process which is applicable for the bioremediation of degraded mine lands. While there are specific plants, known as hyperaccumulators, which can bioaccumulate significantly higher amounts of heavy metals than traditional plants, these plants have high metal specificity and tend to bioaccumulate one specific metal; typically, their biomass has no economic value. On the other hand, there are other high biomass producing plants which, albeit not as efficient as hyperaccumulators, can remediate land in a satisfactory way while also producing products of value such as bioenergy and fibrous biomass.

Thus, for this study, fibre crops are assessed for their potential to provide a renewable raw material or feedstock stream to fuel a multi-product value chain in the context of providing economic complexity in the post-mining economic development of mining regions of South Africa. In order to do so, a general understanding of the mining sites to be remediated, their soil characteristics and climate data is needed. This serves to inform the selection of appropriate fibre crops and is addressed in Chapter 4.

4 A Selection of Fibrous Plants for Phytoremediation and Fibre Production for the Post-Mine Economy in Parts of South Africa

4.1 Characteristics of prevalent mining regions in South Africa

For this study, the focus area was chosen in the region with the highest number of abandoned mines, shown in Figure 4-1, since this region is constituted by large areas of degraded mine land. This also represents the locations in South Africa in which mining is on the decline and the need for a sustained post-mine economy is most pressing. This region has a high population density and includes representation of the main types of mining activities in the country: coal, gold and PGM mining. The characteristics of three mining areas within the selected region are summarised in Table 4-1. Figure 4-2 provides a map of the Köppen climate classification in South Africa.

The Carletonville gold mining area in western Gauteng is contaminated with heavy metals such as Pb (Lead), Ni (Nickel), As (Arsenic), Cd (Cadmium), Cu (Copper), Zn (Zinc), Co (Cobalt) and Hg (Mercury) (LaPerriere *et al.,* 1985; Fashola *et al.,* 2016). Courtman *et al.* (2012) reported that the pH of the soils around Carletonville ranges between pH 5.6 to 6.4, i.e. the area is slightly acidic. The Carletonville area suffers from high acid mine drainage owing to the sulphidic minerals present and high uranium (U) levels (Kings, 2014). The climate in Carletonville is warm and temperate (Cwb) with an average rainfall of 500 - 650 mm with the driest months being during winter (< 10 mm) and the highest rainfall in summer (> 110 mm). The average temperature is 16°C and ranges from 5°C in winter to around 30°C in summer (Saexplorer, 2017; Climate-data.org, 2019).

The metal contamination associated with the coal mines in the eMalahleni region of the Mpumalanga area are Mn (Manganese), Cr (Chromium), Cd (Cadmium), As (Arsenic), Ni (Nickel), Pb (Lead) (Adaikpoh *et al.,* 2006; Pinetown and Boer, 2006; mindat.org, 2019). The topsoil pH is in the range pH 5.5 - 7.2 around the eMalahleni area (Digby Wells Environmental, 2012). The general soil texture in the region is sandy-clay loams (Banks *et al.*, 2011). The eMalahleni region is located in the grassland biome and contains arable soil (Banks and Palumbo-Roe, 2011). The climate in Mpumalanga is warm and temperate (Cfb) with an average rainfall of 600 - 800 mm. The driest months are during winter (< 20 mm) and the highest rainfall is in summer (> 140 mm). The average temperature is 18°C and ranges from 7°C in winter to around 28°C in summer (Saexplorer, 2017; Climate-data.org, 2019).

The Polokwane region in Limpopo is home to a number of platinum mines. The PGMs metals found in this area include Pt (Platinum), Pd (Palladium) and Rh (Rhodium), in relatively lower concentrations. The area also has Au (Gold), Ru (Ruthenium), Ir, (Iridium), Ni (Nickel) and Cu (Copper) (Implants Distinctly Platinium, 2006). The typical soil pH range is from pH 5.5 to 6.4 (Courtman *et al.*, 2012). The dominant soil characteristics around Polokwane are loamy topsoil on rocks, and this has little agricultural potential (Peterson, 2012; Rhengu Environmental Services, 2015). The climate in Limpopo is generally hot and semi-arid (BSh) with an average rainfall of 300 - 500 mm in the Polokwane region with the driest months being during winter (< 5 mm) and the highest rainfall experienced in summer (> 100 mm). The average temperature is 18°C and ranges from 10°C in winter to around 31°C in summer (Saexplorer, 2017; Climate-data.org, 2019).

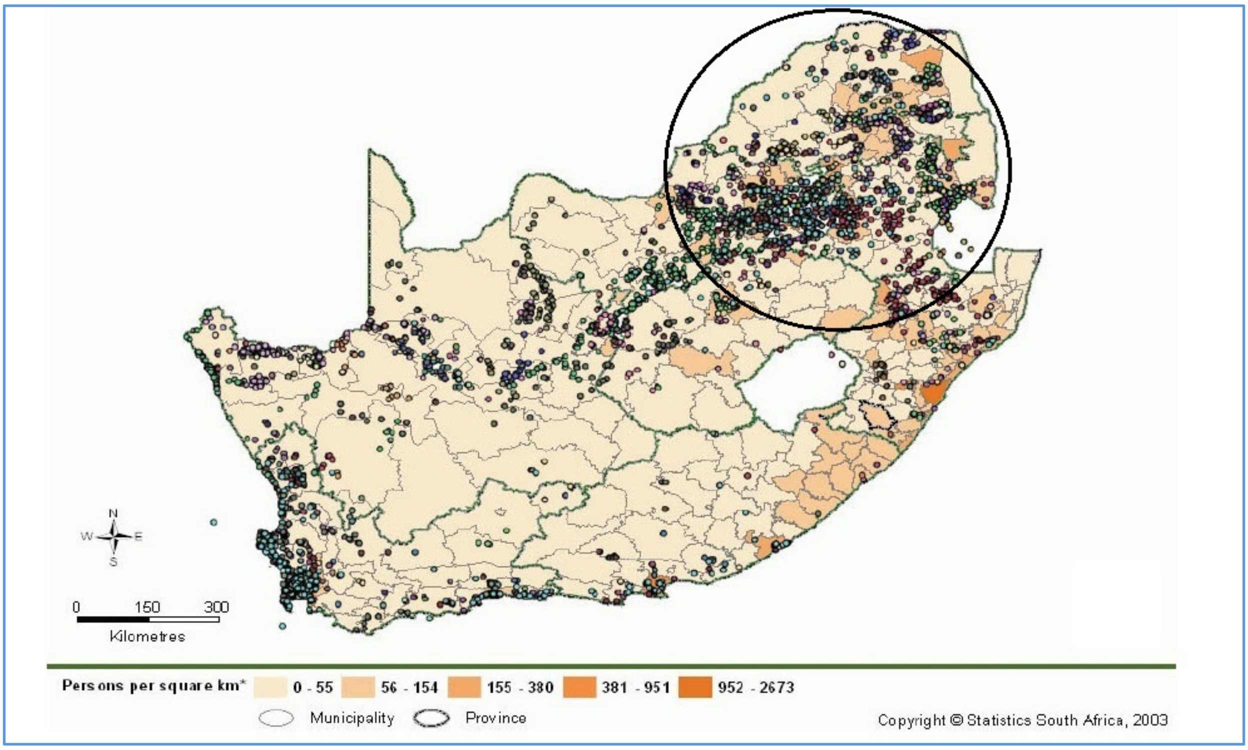

Figure 4-1: Focus area of mining sites for this study adapted from Department of Minerals and Energy (2009)

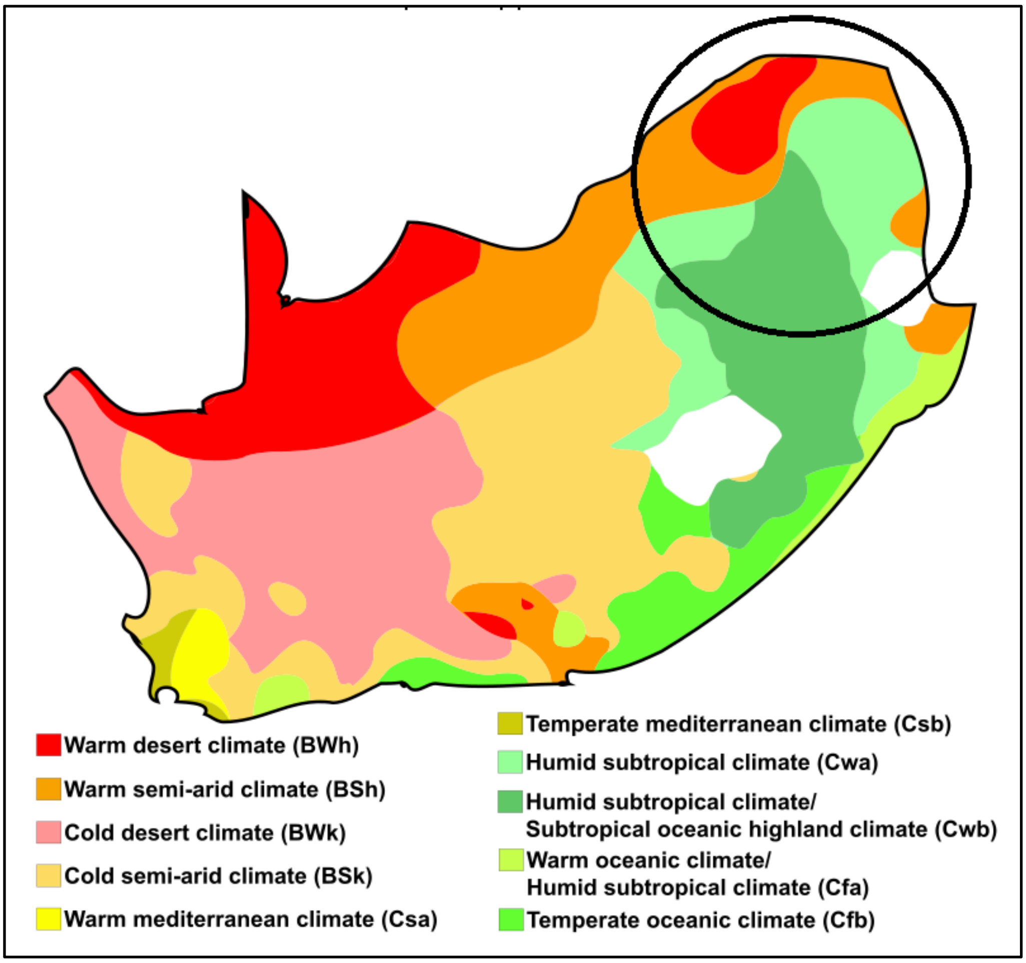

Figure 4-2: South Africa map of the Köppen climate classification (wikimedia commons, 2016)

Table 4-1: Characteristics of mining areas in selected regions

Potential Sites	Target metal or product	Associated metals found	Soil texture	Soil pH	Average rainfall (mm)	Temp (℃)
Carletonville, Gauteng	Gold	Pb, As, Ni, Cd, Cu, Zn, Hg, Co & U	Shallow - rocky	5.6–6.4	500 - 650	5 - 30
Witbank, Mpumalanga	Coal	Al, Ba, Ca, Cl, Cu, Fe, K, Mg, Si, S, N	Sandy-clay loams	5.5–7.2	600 - 800	7 - 28
Polokwane, Limpopo	Platinum	Pd, Rh, Ni, Au, Ir, Cu	Loamy topsoil on rocks	5.5–6.4	300 - 500	10 – 30

4.2 Plant selection

The list of commonly grown fibre crop plants in South Africa presented in Table 3-1 was correlated with the characteristics of mining sites with potential for creation of a post-mining fibre economy presented in Table 4-1. A number of parameters were taken into consideration to narrow down the complete list from Table 3-1. These included the plant's annual rainfall requirement, temperature tolerance as well as availability of prior research done on their phytoremediation potential (Table 3-3). The two main parameters of choice (used as a hurdle for further consideration) were the temperature tolerance and rainfall requirement. Palm, pinewood, baobab, cotton, jute and kapok are plants which usually thrive in hot climates and all the mining sites have temperatures below 10 °C during winter. The mining sites usually have limited rainfall, thus water-demanding plants such as coconut and the bamboo *Dendrocalamus asper* were also not chosen. The remaining plants are the bast fibre crops flax, hemp, kenaf; the leaf crop sisal; and the grass fibre or bamboo crop *Bambusa balcooa*. These show the greatest potential. The bast fibre crops are not water-demanding plants and have high temperature tolerance, especially, kenaf, which also has a high pH tolerance. Much work has been done on the bast fibre crops' phytoremediation potential, especially on hemp and kenaf. This is further discussed in Section 5.2. Sisal is a very sturdy plant and is quite tolerant to regions of low water. *Bambusa balcooa* requires more water than the other four plants but is expected to have access to sufficient water in water-positive regions such as Mpumalanga where water is still pumped.

5 Performance Potential of Selected Plants for the Fibre Economy

5.1 Growth and cultivation of selected plants in South Africa

The growth parameters for the five selected plants are shown in Table 5-1, Table 5-2 and Table 5-3. The following sections give more details on their cultivation for fibre production. Further, current growth initiatives for these crops in South Africa are highlighted. All the selected plants require some fertiliser addition or soil amendment and are usually not tolerant of high salinity.

5.1.1 *Bambusa balcooa*

The type of bamboo mostly suited to Africa is the sympodial (clumping) bamboo which are relatively easy to cultivate. If they are not over-watered and over-fertilised, they have high yields per hectare. The growing area must be kept free from weeds, fallen leaves and culm sheaths. The yield of mature bamboo is around 40 tonnes per hectare per year (from the 5^{th} year onwards) with a one-time planting required as the bamboo's extensive root base sprouts new shoots readily (Fernandes, 2017). The plants have no known pests in South Africa but must be protected from wild animals who can eat the young shoots. Due to the long harvest times of bamboo, young bamboo plants can be intercropped with cash crops for a potential source of revenue for the first two to three years. The majority of bamboo species in South Africa are *Bambusa balcooa*, brought over by Dutch traders. There is a common misconception that clumping bamboo are high water-demanding plants, but this is not usually the case as they are grown in regions of low rainfall (The Biomass Corporation, 2008). Scheda *et al.* (2017) identified seven main bamboo initiatives in South Africa: three in the Eastern Cape, three in KwaZulu-Natal and one in Gauteng, with activities ranging from small experimental cultivation to large-scale plantations for possible fibre and bioenergy production. They suggest that the Eastern Cape and KwaZulu Natal provinces are the most appropriate regions for bamboo cultivation.

5.1.2 Flax

The flax plant grows best in a cool and moist climate. Irrigation is necessary in hot and dry climates. A typical life cycle consists of a 45 – 60 day vegetative period, a 15 – 25 day flowering period and a maturation period of 30 – 40 days (ARC, 2014a). Fibre flax needs at least 110 – 150 mm rain in the vegetation phase. Some 11 – 14 tonnes/ha of seed are required for fibre flax and 5 – 7 tonnes/ha for linseed. It is preferable to do the sowing in rows 8 - 12 cm apart at a depth of 2cm. The general requirement for fertiliser is N-P-K in the ratio 1:2:3 (Cordis, 2016). Around 500 ha of flax was being grown for fibre in the Western Cape for a linen factory, but this factory has since closed down, removing the market (Thompson *et al.,* 2019).

5.1.3 Hemp

Hemp is an annual herbaceous plant with a rapid growth rate and moderate fibre yield. It can reach nine metres in height but is typically cultivated to attain a height of 2 – 4 metres. There are three main groups of *Cannabis* varieties (Thompson *et al.,* 2019):

(i) Fibre: This variety of hemp produces both primary (long, coarse fibres) and secondary (short and fine) bast fibres. These varieties have low concentrations of medicinal and narcotic compounds such as tetrahydrocannabinol (THC).

(ii) Seed: This type of hemp is usually branched and contains 29 – 35% of oil and exhibits low THC.

(iii) Medicinal and narcotic: These plants are branched and accumulate high concentrations of THC and cannabidiol (CBD).

Hemp fibres usually constitute 8.5 – 30% of the total stem mass and are made up of two types of bast fibres: primary (70%) and secondary (30%) bast fibres. The plant requires an annual rainfall of at least 500 – 700 mm and, for optimum yield, 250 – 300 mm of moisture during the vegetative growing stage. It grows best on deep and well-aerated soil with a good water supply, but it is relatively resistant to seasonal water shortages. Due to its rapid growth, hemp requires an adequate supply of nutrients (N-P-K) for good biomass production. Hemp is sensitive to short days and long nights. European cultivars have a critical daylight period of between 14 – 16 hours. A short-day length will inhibit stem growth and fibre production while inducing early flowering. Suitable growth is found in South Africa in summer where there is typically 13 – 14.4 hours of daylight. To optimise fibre production, the vegetative growth period must be maximised and an early planting date (October to November) is recommended to get taller plants with higher fibre yields. Later planting can result in early flowering and poor fibre production. Other factors impacting hemp production are the row spacing and seeding rate because they influence the growth, biomass production and the fibre/seed yield of the plant. Low seeding rate and wide inter-row spacing will result in large branched plants with heavy seeding with lower bast fibre production. The recommended inter-row spacing is 25 – 30 cm with the seeding rate of 60 – 80 kg per ha (ARC, 2014b; Cordis, 2016). The growth of hemp is currently restricted in South Africa due to legislation with production being limited to the company House of Hemp (Moloi, 2017; Thompson *et al.,* 2019).

5.1.4 Kenaf

Kenaf is an annual or short-lived perennial herbaceous plant with a unique combination of bast and core fibres. It is a fast-growing crop with a height of 1.5 - 4. 5 m achieved within 4 - 5 months. Due to its fast growth cycle, it does not require much water (Bledzki and Faruk, 2004; Pickering *et al.,* 2016).

Being a hardy plant, its stalk is resistant to insect damage. It can be grown under a wide range of climatic conditions, is adaptable to various soils and requires minimal chemical treatment. The protein and oil composition of kenaf seed is comparable to cotton seed. While kenaf can grow on a wide range of soils, it is best grown on well-drained and loamy soils. The preferred climate is warm tropical or sub-tropical climate. A good seed-to-soil contact is required for germination. Kenaf is, however, sensitive to frost and it is thus preferable to maintain temperatures above 10 °C when harvesting. For sowing, around 30 - 40 kg of kenaf seed per hectare is advised at a depth of 1 - 4 cm with an optimum soil temperature of 15°C. The density of plants is recommended to be around 60 - 80 kenaf plants per m^2 while maintaining a distance between the rows and distance within the rows of 25 – 35 cm and 2 - 5 cm respectively. Trials of kenaf were done in KwaZulu Natal, North West province and the Eastern Cape. Kenaf was produced commercially on a limited basis (2000 ha) for a processing facility in Winterton in KwaZulu Natal operated by Sustainable Fibre Solutions Pty (Ltd) but currently commercial production has stopped due to the poor quality of the fibres produced and the lack of adequate processing technology (Parlimentary Monitoring Group, 2015; Thompson *et al.*,2019).

5.1.5 Sisal

Sisal is a perennial fibre crop indigenous to Central and South America with a life span of 10 -15 years, depending on the variety. It can be grown in a wide range of weather conditions and is drought resistant. Due to its superficial root system, sisal prefers well-drained light sandy soils and grows poorly on waterlogged soils. Transplanting is usually done at the beginning of the rainy season and the spacing is usually as double rows of (4 X 1) X 1 m with a plant population of around 4000 plants/hectare. There are two areas which are currently investigating the production of sisal in South Africa: near Giyanie in Limpopo and Madikwe in the North West province (Thompson *et al.,* 2019).

Table 5-1: Growth parameters for the cultivation of bambusa balcooa and hemp adapted from Ecocrop (2007b, 2007c)

Bambusa balcooa	Optimal		Absolute			Optimal	Absolute
	Min	**Max**	**Min**	**Max**	**Soil depth**	medium (50 - 150 cm)	medium (50 - 150 cm)
Temperature (° C)	22	28	9	35	**Soil texture**	heavy, medium	heavy, medium
Rainfall (annual) mm	2300	3000	700	4500	**Soil fertility**	high	moderate
Soil pH	5	6	4.5	7.5	**Soil salinity**	low (<4 dS/m)	low (<4 dS/m)
Light intensity	clear skies	cloudy skies	clear skies	light shade	**Soil drainage**	poorly (saturated >50% of year), well (dry spells)	poorly (saturated >50% of year), well (dry spells)
Climate zone	tropical wet & dry (Aw), tropical wet (Ar), subtropical humid (Cf), subtropical dry summer (Cs), subtropical dry winter (Cw)				**Photoperiod**	short day (<12 hours)	
					Crop cycle	min: 300 days; max: 365 days	
Hemp	Optimal		Absolute			Optimal	Absolute
	Min	**Max**	**Min**	**Max**			
Temperature (° C)	15	28	6	32	**Soil depth**	medium (50 -150 cm)	shallow (20 - 50 cm)
Rainfall (annual)	600	1200	350	4000	**Soil texture**	medium, organic	heavy, medium, light
Soil pH	6	7	4.5	8.2	**Soil fertility**	high	moderate
Light intensity	very bright	clear skies	very bright	cloudy skies	**Soil salinity**	low (<4 dS/m)	low (<4 dS/m)
Climate zone	tropical wet & dry (Aw), tropical wet (Ar), steppe or semiarid (Bs), subtropical humid (Cf), subtropical dry summer (Cs), subtropical dry winter (Cw), temperate oceanic (Do), temperate continental (Dc), temperate with humid winters (Df), temperate with dry winters (Dw)				**Soil drainage**	well (spells)	poorly (saturated > 50 % of year), well (dry spells)
					Photoperiod	short day (<12 hours), neutral day (12-14 hours), long day (>14 hours)	
					Crop cycle	min: 90 days; max: 170 days	

Table 5-2: Growth parameters for the cultivation of kenaf and flax adapted from Ecocrop (2007d, 2007e)

Kenaf	Optimal		Absolute			Optimal	Absolute
	Min	**Max**	**Min**	**Max**			
Temperature (° C)	15	28	10	35	**Soil depth**	deep (>> 150 cm)	medium (50 - 150 cm)
Rainfall (annual)	600	2000	450	3000	**Soil texture**	medium, organic	heavy, medium, light
Soil pH	6	7.5	4.3	8.2	**Soil fertility**	high	moderate
Light intensity	very bright	very bright	very bright	cloudy skies	**Soil salinity**	low (<4 dS/m)	low (<4 dS/m)
Climate zone	tropical wet & dry (Aw), tropical wet (Ar), steppe or semiarid (Bs), subtropical humid (Cf), subtropical dry summer (Cs), subtropical dry winter (Cw), temperate oceanic (Do), temperate continental (Dc), temperate with humid winters (Df), temperate with dry winters (Dw)				**Soil drainage**	well (dry spells)	well (dry spells), excessive (dry/moderately dry)
					Photoperiod	short day (<12 hours)	
					Crop cycle	min: 100 days; max: 240 days	
Flax	Optimal		Absolute			Optimal	Absolute
	Min	**Max**	**Min**	**Max**			
Temperature (° C)	16	24	5	30	**Soil depth**	shallow (20 - 50 cm)	shallow (20 - 50 cm)
Rainfall (annual)	500	800	250	1300	**Soil texture**	heavy, medium	heavy, medium
Soil pH	6	6.5	5.5	7	**Soil fertility**	high	high
Light intensity	clear skies	clear skies	very bright	cloudy skies	**Soil salinity**	low (<4 dS/m)	low (<4 dS/m)
Climate zone	desert or arid (Bw), steppe or semiarid (Bs), subtropical humid (Cf), subtropical dry summer (Cs), subtropical dry winter (Cw), temperate oceanic (Do), temperate continental (Dc), temperate with humid winters (Df), temperate with dry winters (Dw)				**Soil drainage**	well (dry spells)	well (dry spells)
					Photoperiod	neutral day (12 - 14 hours), long day (>14 hours)	
					Crop cycle	min: 80 days; max: 180 days	

Table 5-3: Growth parameters for the cultivation of sisal adapted from Ecocrop (2007a)

Sisal	Optimal		Absolute			Optimal	Absolute
	Min	**Max**	**Min**	**Max**			
Temperature (° C)	15	27	10	45	**Soil depth**	medium (50 - 150 cm)	shallow (20 - 50 cm)
Rainfall (annual)	900	1250	500	1800	**Soil texture**	medium light	heavy, medium, light
Soil pH	6	7.5	5.5	8	**Soil fertility**	moderate	low
Light intensity	very bright	clear skies	very bright	cloudy skies	**Soil salinity**	low (<4 dS/m)	low (<4 dS/m)
Climate zone	tropical wet & dry (Aw), subtropical humid (Cf), subtropical dry summer (Cs), subtropical dry winter (Cw)				**Soil drainage**	well (dry spells)	well (dry spells), excessive (dry/moderately dry)
					Photoperiod	short day (<12 hours)	
					Crop cycle	min: 150 days; max: 270 days	

5.2 Fibre yield and phytoremediation potential of selected plants

5.2.1 Fibre production

Table 5-4 gives an estimate of the dry biomass yield, harvest time and fibre yield from the five selected plants. Depending on the cultivars and whether the crops have been genetically modified, the yields can vary substantially. Bast fibres (flax, hemp and kenaf) usually produce long, relatively strong fibres. High quality long flax fibres are used to make linen while shorter fibres can be used in more innovative applications such as packaging and material reinforcements (Paridah *et al.*, 2011). Flax fibres are amongst the strongest natural fibres. Hemp fibres are coarser than flax fibres and are usually more difficult to bleach. Hemp fibres are traditionally used to make textiles, however, new research is focused on biocomposite production (Paridah *et al.*, 2011; Sfiligoj *et al.*, 2013) as well as functional materials. Hemp plants usually grow with higher yields per hectare than flax (Sen and Reddy, 2011).

Contrary to flax and hemp, the characteristics of kenaf fibres are similar to wood. Hence, kenaf can act as substitute raw material for the manufacture of wood-derived products. Novel applications of kenaf focus on the biocomposites industry. Typically, kenaf fibre yields are greater than flax and hemp (Paridah *et al.*, 2011).

The leaf fibres from sisal are hard and coarse with limited flexibility. The lower grade fibres have a high cellulosic and hemicellulosic content and can be used in the paper industry. The medium grade fibres are used in the cordage industry and higher grade fibres are usually converted into yarns and used in the carpet industry (Sfiligoj *et al.*, 2013).

Bamboo fibres demonstrate higher lignin and hemicellulose content than bast fibre crops. The fibre processing is more tedious as a result. The fibre lengths vary considerably among different species (Nayak and Mishra, 2016) . However, *Bambusa balcooa* has a significantly higher biomass production than other species, which gives it a competitive advantage over the four other fibre crop species under study.

Table 5-4: Dry biomass yield, harvest time, fibre yield and potential products of selected plants

Name	Dry biomass (tons/ha)	Harvest time	Fibre yield (tons/ha)	Reference
Bambusa balcooa	20 - 40	5 - 6 years	12 -18[4]	(WenYan and NaiXun, 2003)
Flax	3 - 4.5	80 - 180 days	1 - 2	(Couture *et al.*, 2002; Thompson *et al.*, 2019)
Hemp	10 - 20	90 - 170 days	2.2 - 8.1	(Struik *et al.*, 2000; Burczyk *et al.*, 2008; Russell *et al.*, 2015)
Kenaf	15 - 25	100 - 240 days	5 - 10	(Singh, 2010; Sen and Reddy, 2011)
Sisal	13 -17[5]	2 – 4 years	1 - 4	(Davis *et al.*, 2011)

[4] Bamboo culms usually contain 40 – 60% of fibres and by the 5th year, up to 30 000 kg/ha of culms can usually be harvested, translating to around 12 – 18 tons of fibre/ha

[5] for 3000 plants per hectare

5.2.2 Phytoremediation potential

Hemp is one of the most studied fibre crops for phytoremediation as its roots have a high tolerance to different metals present in the soil. It has been shown to accumulate more than 100 mg/kg Cd in dry tissue (Sanità di Toppi and Gabbrielli, 1999). Angelova *et al.* (2004) investigated the metal uptake in flax, hemp and cotton by growing these plants on land degraded by metal accumulation. The experimental plots (20 m^2) were situated at different distances (0.5 and 15 km) from the source pollution. The experimental plot situated 15 km from the source of metal pollution had a metal concentration about seven times lower than the experimental plot 0.5 km away. The metal concentrations (Pb, Cu, Zn, Cd) were measured in different parts of the crop plants: roots, stems, leaves, seeds, flowers and fibres. They concluded that flax and hemp are suitable crops to remove considerable amounts of heavy metals from polluted soils with their root system. The highest metal concentration was found in the flax roots with 104.4 mg Pb/kg, 30.5 mg Cu/kg and 211.8 mg Zn/kg. The hemp roots contained 38.2 mg Pb/kg, 7.2 mg Cu/kg, 66.8 mg Zn/kg and 1.03 mg Cd/kg. Angelova *et al.* (2004) did suggest a major concern was the metal reporting to the fibres of both flax and hemp which suggested that the fibres should not be used as raw material for textiles. Relative deportment across these plants requires further study. In another study, Ahmad *et al.* (2016) collected hemp plant samples from a metals contaminated site in Pakistan and assayed for metal accumulation in the plant leaves, showing 1530 mg Cu/kg, 151 mg Cd/kg and 123 mg Ni/kg. Shi *et al.* (2012) further investigated hemp's viability and vitality when grown on a soil heavily contaminated with Cd; above a Cd concentration of 800 mg/kg, the plant growth is compromised.

Kenaf is another bast fibre plant on which several phytoremediation studies were done to assess its tolerance to heavy metals and their effect on its high biomass production. A summary of a selection of studies, collated by Bauddh *et al.* (2017), is presented in Table 5-5. Mani *et al.* (2018) studied the Pb phytoremediation potential of kenaf on artificially contaminated soil and they concluded that while kenaf demonstrated good phytoremediation potential, numerous cycles of growth would be needed to remediate the contaminated soils effectively.

Table 5-5: Metal accumulation by kenaf from contaminated soil (Bauddh *et al.*, 2017)

Metal	Soil (mg/kg)	Roots (mg/kg)	Stem (mg/kg)	Leaves (mg/kg)	References
Cd	3.54	2.67	0.37	1.95	(Bettaieb *et al.*, 2013)
Zn	1157	65.33	53.90	60.98	
Cd	3.54	-	1.50	0.99	(Arbaoui *et al.*, 2013)
Zn	1157	-	53.90	23.41	
Cd	6		2.78		(Bada and Raji, 2010)
As	12.31	7.13	0.42	1.31	(Meera and Agamuthu, 2012)
Fe	2231	13710	516	920	
Pb	5	1.50	1.21	1.17	(Bada, 2016)
Cr	5.5	0.15	0.13	0.12	
Zn	27.5	3.18	13.10	23.48	
Cd	0.5	0.14	0.12	0.13	
Zn	4500 µm	285.15	162.9	272.2	(Arbaoui *et al.*, 2014)
Cd	50 µm	40.65	14.09	35.34	

There is limited research on the hyperaccumulating potential of sisal. dos Santos *et al.* (2011) investigated the uptake of Pb and Cd in sisal fibre and determined the biosorption capacity to be 1.85 mg Cd/g and 1.34 mg Pb/g. Based on review of the literature and case studies, Mothapo (2017) proposed a list of bamboo species suitable for rehabilitation of mining sites in South Africa, including both *Bambusa balcooa* and *Dendrocalamus asper*. Similarly Sims (2011) from Virtual State Solutions (Gauteng) highlighted the phytoremediation potential of *Bambusa balcooa*. However, none of these studies presented concentrations of metal uptake achieved. The bamboo species which is generally considered globally for phytoremediation is the *Moso* bamboo. Various studies have reported phytoremediation potential of *Moso* bamboo for Cd, Pb, Zn, Cu (Liu *et al.*, 2014; Li *et al.*, 2017). However, as this species is invasive in South Africa, it is not considered further.

Metal accumulation data tend to show variation between studies since the environmental conditions, soil cultivation and cultivars studied influence the phytoremediation potential of plants. However, in general, two major concerns require careful and rigorous investigation to allow finalisation of the proposed route for development of a fibre-based economy, underpinned by economic complexity.

Firstly, the potential for metal accumulation in harvestable parts of the plants must be assessed for the specific applications considered as such accumulation will limit the products which can be manufactured from the fibrous biomass and may demand a two-stage development process for the fibre economy. Secondly, the productivity of some fibre crops is negatively affected by high levels of pollutants and thus the extent of pollution, the inter-dependence of growth conditions, plant species and impact of pollutant on the biomass productivity play a crucial factor in the selection of the appropriate plant-application pair for the fibre economy. Similarly, extreme cases of pollution may require a two-stage development process for the fibre economy.

5.3 Growth limitations of fibre crops on highly degraded mine land

The level of pollution on degraded mine lands may impact the growth of fibrous plants and the quality of fibres as highlighted in Section 5.2.2. Fibre crops are expected to grow better in low to moderately contaminated soil. For heavily contaminated mine lands, the soil quality is usually very poor with a high concentration of metals, limited topsoil and, potentially, salinization and low pH due to acid mine drainage. In acidic soils with a lack of organic matter, the diversity of microbial communities is also reduced (Wong, 2003; Wang *et al.*, 2007; Mensah, 2015), negatively impacting bioavailability of nutrients. Attempting to grow fibrous plants directly on this type of land is not recommended, unless the growth system has been demonstrated to tolerate these conditions specifically. Instead, it is recommended to first remediate or partially remediate the site before commencing with the fibrous plant cultivation i.e. the two-stage process discussed above.

There are a number of available ways to improve the soil quality. These include physico-chemical restoration and biological restoration. However, biological restoration requires acclimatised hyper-accumulators. Physical restoration can be done by adding topsoil, which can be moved from nearby areas. Another possible way to increase the organic content of the soil is to mix in organic residues. One of the least expensive and most effective methods to immobilise heavy metals and improve the soil quality is the combined use of biochar and compost (Kumpiene *et al.,* 2008; Farrell *et al.*, 2010; Beesley *et al.*, 2011). If the soil remains too acidic, chemical restoration in the form of fertilisers can be used. For appropriate biological restoration, a stable plant cover such as hyperaccumulators is advised to clean up the land as discussed previously.

6 Findings and Recommendations

6.1 Findings

With the increasing expectation of mine closures in key mining regions in South Africa over the coming years as resources become depleted, as well as the high (and growing) prevalence of abandoned mines over the past 30 years, it is critically important to address both the environmental legacies of the post-mine environment and to generate replacement post-mine economies for the settlements in these regions. Furthermore, it is increasingly recognised as necessary to seed the bases of these post-mine economies during the life-of-mine to enable their establishment during the wealth generation phase of the mine.

Unused mine lands, often abandoned and left derelict leading to severe environmental and socio-economic impacts, provide a resource for this post-mine economy. It is recognised that simple remediation is costly and typically does not offer a sustainable environmental solution. Further, there is a need to develop alternate economic activities to support the livelihoods of those in the surrounding communities impacted by mine closure. There exists an opportunity to transform degraded land into a remediated, productive resource from which to generate economic outputs. In this community of practice, we explore the re-purposing of degraded mine land to produce renewable fibre crops to support a fibre economy demonstrating economic complexity, with associated robustness and potential wealth creation. In this working paper, we address the potential of the remediation of the land and concomitant establishment of a renewable raw material or feedstock for this fibre economy.

To ensure this transformation is successful, there are various factors which need to be taken into consideration. Firstly, a cost-effective remediation or, preferably, reclamation approach is needed to reduce the metal concentration of the polluted land, re-establish a good quality soil and ensure an adequate soil microbiome to support the planned agriculture. Secondly, renewable feedstock generation through cultivation of these lands is required. Thirdly, a viable income-generating economy is needed to support the local communities and provide sufficient potential for wealth creation to raise quality of life. In this study, fibre crops were proposed to perform the dual role of the first two steps and provide the raw material base for the third. Fibre crops were chosen owing to the wide range of products of varied complexity and value which can be derived from them and have potential to add to the economic complexity of this proposed system. Further, the literature suggests that these crops demonstrate phytoremediation potential for the remediation and reclamation of polluted land.

To identify suitable fibre crops, the soil characteristics and climate data for key mining regions demonstrating a high number of abandoned mines with further mines approaching end-of-mine-life were selected. These areas were also characterised by high population densities. Within these, possible sites of study were chosen. These site characteristics were used to identify appropriate crops. The growth requirements and parameters of the most commonly grown fibre crops in South Africa were also researched and five plant species were chosen as suitable candidates: the bamboo species *Bambusa balcooa*, flax, hemp, kenaf and sisal. Typical productivity levels for these crops as well as the yield and characteristics of fibre components of the biomass formed were considered.

The bast fibre crops (flax, hemp, kenaf) usually yield high fibre quality. However, like all bamboo species, *Bambusa balcooa* demonstrated a much higher biomass production potential and thus a higher fibre yield per hectare. Another distinction among the plants is that while the bast fibre crops are annual, bamboo and sisal are perennial plants. Where perennial plants are used, fibre harvesting can only start after a few years, but repeat planting is not required.

The phytoremediation potential of these crops was researched through literature studies. Flax, hemp and kenaf demonstrate high potential for metal removal and accumulation. While previous studies identified *Bambusa balcooa* as a good bamboo candidate for phytoremediation in South Africa, it is not among the most studied species globally, hence reliable metal uptake data were missing. Phytoremediation data for sisal was also scarce. Additional research is required to define sisal's metal uptake potential and the zone of accumulation of the metals.

Initial quantitative studies have demonstrated the potential for the approach of fibre crops to yield both a raw material stream and to remediate or reclaim the lands, with increasing potential for an expanded crop range. Potential may exist to also recover a metal product.

Several challenges require careful assessment on a case-by-case basis prior to commercial implementation of fibre plant cropping on degraded mine land. The level of pollution of the degraded mine land is a determining factor on the growth viability of fibre crops and their productivity. Where it is desirable to use highly contaminated land, soil quality may first need to be improved to support fibre crops' growth. It is expected that the phytoextraction of metals by the fibre crops will proceed more slowly owing to their lower accumulation of metals in comparison to hyperaccumulators, thus requiring more crop harvests. Further, depending on the plant species, metals accumulate in different parts of the plant. Where metals accumulate in the stems to a significant degree, fibre quality may be compromised and, in some cases, the quality or safety of the end-products. This will inform against crop selection or require an additional remediation phase such as biological restoration with hyperaccumulators to precede the production of fibre crops.

6.2 Conclusions and recommendations

The purpose of this study was to demonstrate the potential that fibre crops hold with respect to the provision of a renewable raw material for the fibre economy while simultaneously ensuring the transformation of degraded mine land and its reclamation as high-quality agricultural land. This was approached as a feasibility study collating data from mine sites with growth requirements and productivity of fibre plant species, with data gathered from different literature sources. The main finding was that fibre crops have the ability to grow over a diverse range of climatic conditions and land qualities. Degraded land with low or medium levels of metal contamination is expected to sustain fibre crops, with plant yields impacted by the level of contamination, and so produce the raw materials for manufacturing processes to produce value-added outputs. How efficiently this can be achieved is impacted by multiple factors and requires a number of case-specific studies. This is proposed in the ongoing work planned through both site-specific desktop studies and field-based growth studies.

The extent of pollution of the sites considered for combined remediation and multi-product development is a key factor in expected performance. Based on the extent of soil contamination, an informed decision can be made on which fibre crop to use and whether a fibre crop will suffice to tackle both remediation and generation of renewable fibre-based feedstock simultaneously to contribute to a post-mining economy. In cases of heavily contaminated land, it is recommended that hyperaccumulators be used first to ensure the maximum rate and extent of metal extraction and associated valorisation by phytomining, prior to progressing to the proposed dual system for land reclamation and raw material production. Fibre crops can then be grown on the less contaminated land for better plant growth and fibre quality. Here again, experimental and field work is recommended to further investigate the feasibility of the proposed approach.

7 References

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