

Exploring the use of indigenous Western Cape plants as potential water and soil pollutant phytoremediators with a focus on green infrastructure

DM Jacklin¹, IC Brink¹ and SM Jacobs²

¹Department of Water and Environmental Engineering, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa

²Department of Conservation Ecology and Entomology, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa

Urban water managers, engineers and conservation ecologists in the Western Cape (WC) Province of South Africa are faced with a major environmental and human health challenge, with urbanisation, industrialisation, population growth and agricultural development placing pressure on the limited water and soil resources. In addressing this resource degradation an effective, affordable and sustainable solution is required. The implementation of 'green infrastructure' (GI), such as phytoremediation, involves the use of plants to hinder pollutant transport and attenuate runoff flow, protecting the health of the human population and the environment. However, care must be taken when selecting plant species due to possible invasive behaviour, affecting ecosystem dynamics. As a result of the need for resource remediation in both urban and rural areas, the use of non-invasive indigenous species is vital to an efficient and sustainable technology, as urban areas are often the initial sites for introduction from which invasions spread. This paper proposes indigenous WC species for potential use in GI, identified from global bioremediation literature, as an aid to the practicing civil engineer and water manager responsible for the design and management of the phytotechnology. These indigenous species offer potential as phytoremediators in local GI, as well as suggest the types of plants that should be investigated further as alternatives to effective exotics. The investigation returned 56 non-invasive WC plant species likely to aid resource remediation without jeopardising the conservation and biodiversity of the administered area. The selected vegetation is potentially capable of increasing heterogeneity and adjusting to the dynamic biogeographic conditions of the recipient habitat. Thus, distinct species capable of remediating a wide range of environmental contaminants for GI, into the diverse habitats of the WC, at a fraction of the cost of conventional techniques, are promoted.

CORRESPONDENCE

IC Brink

EMAIL

icbrink@sun.ac.za

DATES

Received: 8 September 2020

Accepted: 3 July 2021

KEYWORDS

Green infrastructure
phytoremediation
phytotechnologies
water quality
ecological engineering

COPYRIGHT

© The Author(s)
Published under a Creative
Commons Attribution 4.0
International Licence
(CC BY 4.0)

INTRODUCTION

Persistent and excessive release of heavy metal, organic and inorganic pollutants from anthropogenic activities is blamed for destroying entire natural ecosystems, posing a major human and environmental health problem (Cunningham et al., 1995; Salt et al., 1995; Dhir et al., 2009; Abhilash et al., 2012; Choudhary et al., 2015; Tripathi et al., 2015). The Western Cape (WC) Province of South Africa has been subjected to similar deleterious impacts, with increased urbanisation, high population growth, agricultural development, dysfunctional water and wastewater treatment works, and industrialisation placing enormous pressure on the limited soil and water resources (Giliomee, 2006; Nomquphu et al., 2007).

The widespread contamination of soil, a non-renewable natural resource in the short term and very expensive to reclaim once physically or chemically degraded, has for decades been a global remediation and management challenge (Ali et al., 2015; Rada et al., 2019). This rampant degradation is evident with more than 25% of global soil resources highly degraded and roughly 44% moderately degraded, predominantly as a result of pollution (Peuke and Rennenberg, 2005). Alarming, South Africa is recognised as one of the regions experiencing the most rapid environmental degeneration (Abhilash, 2015). The WC receives various pollutants of anthropogenic origin to the soils, which include significant amounts of bioavailable heavy metals (Schloemann, 1995), fertilisers, pesticides, herbicides and fungicides (Malan et al., 2015), as well as stormwater, wastewater and sewage runoff (Chen et al., 2008; Müller et al., 2014).

Similarly, pollutant deposition deteriorates water-quality in urban and rural watercourses and groundwater aquifers, raising a plethora of public and environmental health concerns (Constantine et al., 2014; Sibanda et al., 2015; Pakdel and Peighamardoust, 2018). In South Africa, main rivers classified as having a poor ecological condition increased by 500% between 1999 and 2011, with some beyond the point of recovery, posing a threat to the country's potable water resources (Oberholster and Ashton, 2008; DWS, 2018). This is as a result of the nationwide failure to properly treat wastewater, where 56% of the sewage treatment works are failing and 11% are dysfunctional (DWS, 2018). De Villiers and Thiart (2007) found that 6 of the 20 largest river catchments in South Africa that are under eutrophication are located in the WC. In addition, the findings of Musingafi and Tom (2014) and Milandri et al. (2012) point to the fact that urban effluent discharge contributes a wide range of pollutants to freshwater ecosystems.

Green infrastructure (GI) is the interconnected set of natural and engineered ecological systems providing environmental services (Fletcher et al., 2015). In comparison with traditional grey infrastructure, these systems have been found to reduce financial costs by up to 42% (Vineyard et al., 2015). These systems offer a novel and sustainable approach to polluted water and soil systems,

reducing pollutant transport and reducing resource toxicity, by combining resource remediation with sustainable civil engineering methods (Choudhary et al., 2015; Kondo et al., 2015; Malan et al., 2015; Malherbe et al., 2018). The GI engineered approach has the ability to complement or replace existing technological or grey infrastructure designs, presenting a more cost-effective, self-sustaining and versatile long-term alternative (Nel et al., 2014). In South Africa, GI is currently an under-realised asset (DWS, 2018).

Critical to GI efficiency, phytoremediation uses appropriately selected plants for the in-situ treatment of environmental contaminants from soils, sediments and water (Terry and Banuelos, 1999; Dietz and Schnoor, 2001; Visoottiviset et al., 2002; Peuke and Rennenberg, 2005; Payne et al., 2014). A large number of plants possess potential to detoxify, degrade and/or remove pollutants from the environment, and have gained importance globally, receiving significant scientific and commercial attention (Salt et al., 1998; Gleba et al., 1999; Guerinot and Salt, 2001; Krämer and Chardonnens, 2001; Meagher, 2000; Peuke and Rennenberg, 2006). This green engineering solution is popular due to its cost-effectiveness, aesthetic advantages, long-term applicability, employment generation capacity and scope of pollutant remediation efficacy (Raskin et al., 1994; Abhilash, 2015; Marrugo-Negrete et al., 2015). Although effective, plants and their rhizosphere organisms phytoremediate in different ways, with various mechanisms suitable for different pollutants (Read et al., 2010). The use of field and vegetable crops cultivated for commercial use as phytoremediators has proven valuable in bioremediating municipal and industrial discharge from failing sewage treatment works, as well as rehabilitating old and abandoned mining sites (Poonam et al., 2014; Rizwan et al., 2016).

In designing a sustainable GI remediation technology, the responsible engineer must assess the potential adverse impacts induced by the introduction of chosen effective pollutant-specific remediators, based on the findings of previous investigations (Leguizamo et al., 2017). Prior to plant selection for use in remediation projects, the ecosystem-related and ecological functions of the plants need to be established (Budelsky and Galatowitsch, 2004). For instance, failure to consider invasion threat may lead to creating an artificial or altered environment in which alien species thrive (Castro-Diez et al., 2014). In particular, remediation measures must endeavour to utilise plants that are indigenous to the site, in an attempt to return the resource to a sustainable state (Peer et al., 2005). A practicing civil engineer who lacks expertise in plant behaviour or ecosystem dynamics which regulate plant's potential future invasiveness in phytogeographic environments may be ill-equipped to design an effective yet sustainable engineered remediation technology.

It is for this reason that this study focused on indigenous plant species naturally occurring in the WC for potential use in pollutant bioremediation technologies. The plants were selected on the basis of their presence in global phytoremediation literature, phytogeographic distribution, conservation status and invasiveness. This article discusses the phytoremediation process and WC vegetation whilst emphasising the impact their introduction may have on the recipient ecosystem. Finally, after investigating plant species from relevant literature, potential indigenous species and cultivated crops effective for GI technologies in the WC are recommended.

Phytoremediation processes within green infrastructure engineering

The term phytoremediation is applied to a technology that makes use of both wild and transgenic plant species for the treatment

of contaminated soils, sediments, water and air, with the aim to effectively restore, protect or ameliorate environmental degradation by removing pollutants or rendering them harmless (Salt et al., 1998; Terry and Banuelos, 1999; Dietz and Schnoor, 2001). These pollutants are predominantly generated by agricultural and industrial products and practices, urban pollution, stormwater runoff and defective wastewater treatment facilities (Khan et al., 2000). All plants have the ability to accumulate heavy metals that are essential for growth and development from soil and water, including Cu, Fe, Mg, Mn, Mo, Ni and Zn, with some plants able to accumulate heavy metals such as Ag, Cd, Co, Cr, Hg, Pb and Se, that offer no biological function (Dhir et al., 2009). Various phytoremediation processes exist, making use of different species of plants for each contaminant (Cunningham et al., 1997; Dietz and Schnoor, 2001). There is, however, a limit to the extent to which plants can accumulate these metals, beyond which they become toxic, with plants varying in removal efficiency and tolerance (Read et al., 2010). The intricate planning and design of GI technologies must consider both the type of pollution and habitats of the specific site, to appropriately identify and select potential species for optimised phytoremediation. Therefore, the use of non-invasive species, adept at remediating the pollution at hand whilst limiting the risk of biodiversity loss, should always be promoted (Payne et al., 2015). Numerous laboratory and field assessments have developed a better understanding of heavy metal, petrochemical, ammunition waste, chlorinated solvent, landfill leachate, non-point source agricultural runoff (pesticides and fertilisers) and urban stormwater runoff phytoremediation (Salt et al., 1995; Chaney et al., 1997; Macek et al., 2000; Pilon-Smits, 2005; Abhilash et al., 2012; Milandri et al., 2012). GI capitalises on the innate abilities of photosynthetic plants to eliminate a variety of pollutants, by destruction, inactivation, extraction, volatilisation or immobilisation, with some extracted metals even recycled for value (Raskin et al., 1994; Peuke and Rennenberg, 2006; Leguizamo et al., 2017).

The effect of biological invasion

Biological invasions alter the structure and function of the natural ecosystem, causing the loss of an ecoregion's characteristic species, and may result in loss of indigenous biota (Yang et al., 2015). South Africa has a long history of plant introduction and invasion transforming ecosystems, posing a major threat to the country's biodiversity, impacting negatively on the ecosystem's capacity to deliver goods and services, and in some cases severely threatening human livelihoods (Le Maitre et al., 2020). Alien plant invasion costs the country 2 billion ZAR annually for its control (Van Wilgen et al., 2020; Zengeya and Wilson, 2020). This widespread degradation is particularly evident in the WC Province with the most extensive as well as the greatest number of invasive species, notably reducing the value of fynbos ecosystems by over 195 billion ZAR due to a loss in ecosystem services (Van Wilgen et al., 2001; Pyšek and Richardson, 2010; Van Wilgen et al., 2020).

The WC is home to 70% of the Cape Floristic Region (CFR), recognised as one of the richest habitats in the world, regarding its floristic heterogeneity and endemism (Von Hase et al., 2003). With a prominent diversity of over 9 000 species of which 70% are endemic, the CFR is one of only 25 globally accepted biodiversity hotspots (Giliomee, 2006). For its tiny size, the area most likely has the richest flora worldwide (McDowell and Moll, 1992).

METHODOLOGY

This paper investigated 800 literature sources to guide the selection of proven effective phytoremediation species for potential use in GI technologies in the WC. In compiling a list of potential phytoremediators, peer-reviewed articles, books, reports, case

studies, conference proceedings, theses and dissertations, as well as online databases, were investigated. The findings related to various studies of bioremediation initiatives for stormwater quality improvement, sustainable urban drainage systems, water-sensitive urban designs, water and soil rehabilitation initiatives and plant affinity for heavy metal accumulation. From these findings, potential endemic and indigenous candidates for the WC were identified by comparing herbarium records from the South African National Biodiversity Institute's Red List of South African Plants (SANBI) and Plants of Southern Africa (POSA), Plants of the Greater Cape Floristic Region (PGCFR), and Stellenbosch University Botanical Garden (SUNBG) with the species from literature. Plants displaying invasive characteristics, whose introduction may threaten the sustainability of a phytoremediation project and increase ecosystem vulnerability, were excluded, based on local and international standards. Regional and online records from the Centre for Agriculture and Bioscience International Invasive Species Compendium (CABI), the Global Invasive Species Database (GISD), the Alien Invasive Plant List for South Africa (AIPLSA), the National Environmental Management: Biodiversity Act, 2004 – Alien and Invasive Species List (NEM:BA A&IS), the Status of Biological Invasions and their Management in South Africa (SBIMSA), Biological Invasions in South Africa (BISA), the Information Retrieval and Submission System of the Centre for Invasion Biology (CIB) and the South African Plant Invaders Atlas (SAPIA), also provided a basis for exclusion of certain plants.

By considering existing recommendations and reported presence in literature, spatial distribution, invasive threat and vulnerability to extinction, erroneous introduction of potential plants into engineered designs and natural ecosystems is minimised.

RESULTS AND DISCUSSION

The investigation delivered 1 410 plant species, from 582 genera with 136 subspecies and variations, for potential use in GI phytoremediation initiatives. Analysis returned 257 indigenous and naturalised South African plant species of which 174 were distributed phyto-geographically throughout the WC Province. Of the species, 80 were found to be registered as either endemic or indigenous to the province, with 56 of these regarded as non-invasive and of least conservation concern (Table 1). These plants are likely to aid remediation without jeopardising the conservation and biodiversity of the recipient ecoregion. In reporting, emphasis is placed on effective phytoremediators, their distribution as endemics or indigenous to the WC, conservation status and invasiveness.

Of the 56 phytoremediators, 3 are endemic, and 53 are indigenous to the WC. None of the species are registered as invasive to the WC. The list includes both aquatic and terrestrial plants with varying seasonal activity, which benefit GI initiatives, by resisting dormancy during periods of drought. Although the species listed are registered as non-invasive, caution must be taken when introducing plants, as they may with new evidence be found to threaten the sustainability of the recipient ecosystem. In addition, the behaviour of non-endemic species should be assessed prior to introduction in recipient habitats, whereafter approval from relevant ecologists must be sought. The practising civil engineer is cautioned to enlist the help of plant experts when choosing a species for application in GI.

Phytoremediation and Western Cape vegetation

The results showed several WC plant species that are effective across a range of pollutants, which include urban and rural stormwater runoff, agricultural effluent in the form of pesticides, herbicides and fertilisers, heavy metals, explosives

and ammunition wastes, radionuclides, organic pollutants, carcinogenic air, water and soil, chlorinated aliphatic hydrocarbons, petroleum contaminants, domestic and industrial wastewater effluent, landfill leachate, sewage discharge and tannery waste. The list in Table 1 includes 10 endemic South African species, which are: *Agapanthus africanus*, *Agapanthus praecox* subsp. *minimus*, *Arctotis acaulis*, *Aristea capitata*, *Berkheya zeyheri* subsp. *rehmannii* var. *rogersiana*, *Carpobrotus edulis* subsp. *edulis*, *Carpobrotus edulis* subsp. *parvifolius*, *Cyperus textilis*, *Elegia tectorum* and *Prionium serratum*. The number of endemics, in proportion to total indigenous species identified, suggests immense potential for South African phytoremediators yet to be investigated, specifically in the WC, which offers unparalleled biodiversity richness.

The risk of invasive plants in green infrastructure

The use of non-invasive indigenous plants in bioremediation technologies supports plant acclimatisation, alleviates specimen sourcing and contributes to ecosystem conservation initiatives, bolstering the biodiversity and heterogeneity of a habitat by limiting exposure to invasive species. A dynamic resident biota influenced by natural factors, as well as the recipient site's conditions, must be accounted for in order to determine potential invasiveness of introduced species. Thus, consultation with a number of disciplines within science and engineering is imperative to promote an amalgamation of knowledge for the creation of a sustainable design science for GI.

From the findings, some species can be selected based upon their aggressive growth properties and hardiness, common traits shared among efficient remediators. The species demanding caution are *Ceratophyllum demersum*, *Panicum repens*, *Phragmites australis* and *Pteris cretica*, which have been identified as prospective problematic species. This, however, does not excuse caution for the remaining plants, which may be classified as invasive with new evidence. The traits linked to invasiveness in ecosystems, mirrored in traits supporting phytoremediation efficiency, e.g., rapid growth and spread, hardiness and disease and pest resistance, as well as interactions with resident biota in prevailing environmental conditions, were considered (Le Roux et al., 2020).

In investigating WC crops, 8 species were identified for potential phytoremediation from reported literature (not shown). These species are *Beta vulgaris* subsp. *vulgaris*, *Brassica rapa* subsp. *rapa*, *Cannabis sativa*, *Daucus carota* subsp. *sativus*, *Linum usitatissimum*, *Nicotiana tabacum*, *Sorghum bicolor* and *Vigna unguiculata* subsp. *protracta*. Although the WC crops offer prospects for phytoremediation, it is the authors' opinion that they should not be considered for animal feed or human consumption, pending continuation of research on environmental toxin accumulation. The removed toxins are stored in different vascular compartments of the plant until mortality (Vamerali et al., 2010). During cultivation, these toxins may still pose a threat to environmental and human health (Khan et al., 2015). For a site exposed to extreme contamination, the use of cultivated crops can, however, mitigate the immediate environmental threat, supporting their inclusion as potential remediators.

Various environmental factors to consider that contribute to a dynamic ecosystem include nitrogen pollution, atmospheric carbon dioxide concentration, inter-species interactions, and rhizospheric fluctuations due to pollutant deposition. The climate change scenario assessing future vulnerability in a dynamic environment seeks to mitigate plant characteristic adaptations of introduced species. Reported non-invasive species may exhibit greater aggressiveness and, with new evidence, be designated as invasive, which may warrant their exclusion for use in green infrastructure initiatives. Selection of plants for

Table 1. Potential indigenous WC phytoremediation plants of least conservation concern and minimal biological invasive threat

Species	Common name	SA Endemic	WC distribution		Pollutants	Reference
			Endemic	Indigenous		
<i>Agapanthus africanus</i>	Agapanthus	x	x	x	Petroleum	Tsao and Tsao, 2003; Famulari, 2011
<i>Agapanthus praecox</i> subsp. <i>minimus</i>	n.a.	x			NH ₃ , NO ₃ ⁻ & PO ₄ ³⁻	Milandri et al., 2012
<i>Alectra sessiliflora</i>	Verblommertjie			x	Co & Cu	Brooks et al., 1986; Baker and Brooks, 1989
<i>Arctotis acaulis</i>	Renoster Marigold	x		x	NH ₃ , NO ₃ ⁻ , PO ₄ ³⁻ & glyphosate	Jacklin et al., 2020
<i>Aristea capitata</i>	Blue Sceptre	x		x	NH ₃ , NO ₃ ⁻ , PO ₄ ³⁻ & glyphosate	Jacklin et al., 2020
<i>Berkheya zeyheri</i> subsp. <i>rehmannii</i> var. <i>rogersiana</i>	n.a.	x		x	Ni & Se	Przybylowicz et al., 2001; Groeber et al., 2015; CMLR, 2017
<i>Biotiella glabra</i>	n.a.			x	Cu & Zn	Mkumbo et al., 2012
<i>Bolboschoenus maritimus</i>	Sea Club-rush			x	NH ₃ , NO ₃ ⁻ , PO ₄ ³⁻ & glyphosate	Jacklin et al., 2020
<i>Bulbine frutescens</i>	Snake Flower			x	Petroleum	Tsao and Tsao, 2003; Famulari, 2011
<i>Carpobrotus edulis</i> subsp. <i>edulis</i>	Hottentots Fig	x		x	NH ₃ , NO ₃ ⁻ & PO ₄ ³⁻	Milandri et al., 2012
<i>Carpobrotus edulis</i> subsp. <i>parvifolius</i>	n.a.	x		x	NH ₃ , NO ₃ ⁻ , PO ₄ ³⁻ & glyphosate	Jacklin et al., 2020
* <i>Ceratophyllum demersum</i>	n.a.			x	As, Cd, Cr, Cu, Ni & Pb; explosives; radionuclides; organophosphorus, organochlorine & chlorobenzenes	Dietz and Schnoor, 2001; Dhir et al., 2009; El-Khatib et al., 2014
<i>Chlorophytum comosum</i>	Bracket Plant			x	C; CO; formaldehyde; toluene & xylene	Wolverton and Wolverton, 1993; Wolverton and Wolverton, 1996
<i>Cladium mariscus</i> subsp. <i>jamaicense</i>	Saw Grass			x	Al, Fe, Mg & Mn	Schachtschneider et al., 2010
<i>Conyza scabrada</i>	Bakbesembossie			x	Cu & Zn	Mkumbo et al., 2012
<i>Cotula coronopifolia</i>	Brass Buttons			x	Heavy metals & sewage effluent	Finlayson and Mitchell, 1982; Leguizamo et al., 2017
<i>Cyperus difformis</i>	Smallflower			x	Cd, Ni & Pb	Ewais, 1997; Leguizamo et al., 2017
<i>Cyperus dives</i>	Ikhwane			x	NH ₃ , NO ₃ ⁻ & PO ₄ ³⁻	Wright et al., 2017; Frenzel, 2018
<i>Cyperus fastigiatus</i>	Mothoto			x	NH ₃ , NO ₃ ⁻ & PO ₄ ³⁻	Wright et al., 2017
<i>Cyperus textilis</i>	Umbrella Sedge	x		x	NH ₃ , NO ₃ ⁻ , PO ₄ ³⁻ & glyphosate	Wright et al., 2017; Jacklin et al., 2020
<i>Dodonaea viscosa</i>	Sand Olive			x	Al, Cd, Cr, Cu, Mn, N, P, Pb & Zn	Read et al., 2008; Read et al., 2010
<i>Elegia tectorum</i>	Dekriet			x	NH ₃ , NO ₃ ⁻ & PO ₄ ³⁻	Milandri et al., 2012
<i>Eleocharis limosa</i>	Schrad			x	NH ₃ , NO ₃ ⁻ , PO ₄ ³⁻ & glyphosate	Jacklin et al., 2020
<i>Ficinia nodosa</i>	Vleibiesie			x	Al, Cd, Cr, Cu, Mn, N, P, Pb, & Zn; NH ₃ , NO ₃ ⁻ & PO ₄ ³⁻	Read et al., 2010; Milandri et al., 2012
<i>Gerbera jamesonii</i>	Barberton Daisy			x	Benzene, TCE, formaldehyde	Famulari, 2011
<i>Gunnera perpensa</i>	Rivierpampoep			x	NH ₃ , NO ₃ ⁻ & PO ₄ ³⁻	Wright et al., 2017
<i>Juncus effusus</i>	Common Rush			x	Al, As, Cd, Co, Cr, Cu, Fe, K, Mn, Ni, Zn; NH ₃ , NO ₃ ⁻ & PO ₄ ³⁻ ; anthracene & mine effluent	Deng et al., 2004; Leguizamo et al., 2017; Schachtschneider et al., 2017
<i>Juncus kraussii</i>	Dune Slack Rush			x	NH ₃ , NO ₃ ⁻ , PO ₄ ³⁻ & glyphosate; N	Payne et al., 2014; Jacklin et al., 2020
<i>Juncus lomatophyllus</i>	Leafy Juncus			x	NH ₃ , NO ₃ ⁻ , PO ₄ ³⁻ & glyphosate	Frenzel, 2018; Jacklin et al., 2020
<i>Kyllinga brevifolia</i>	Green Kyllinga			x	Ba, Ni, Pb, Sr, Th & U; PAHs	Li et al., 2011; Leguizamo et al., 2017
<i>Leersia hexandra</i>	Rasp Grass			x	Cd, Cr, Cu, Pb & Zn	Deng et al., 2004; Zhang et al., 2007; CMLR, 2017
<i>Lemna gibba</i>	Duckweed			x	As, Cd, Ni & U; radionuclides; Phenol & 2,4,5-trichlorophenol	Mkandawire and Dudel, 2005; Dhir et al., 2009

n.a. = not available

Table 1 Continued. Potential indigenous WC phytoremediation plants of least conservation concern and minimal biological invasive threat

Species	Common name	SA Endemic	WC distribution		Pollutants	Reference
			Endemic	Indigenous		
<i>Lemna minor</i>	Duckweed		x		As, Ba, Cd, Cr, Cu, Fe, Hg, Pb, Ni, Se & Zn; petroleum; radionuclides; wastewater effluent; 2,4,5-trichlorophenol, halogenated phenols; isoproturon, glyphosate; landfill leachate	Bonomo et al., 1997; Vardanyan and Ingole, 2006; Dhir et al., 2009
<i>Mentha aquatica</i>	Aromatic Thyme		x		Cd, Cu, Fe, Ni, Pb & Zn	Dhir et al., 2009; Branković et al., 2012
<i>Mentha longifolia</i> subsp. <i>polyadena</i>	Wild Spearmint		x		Cr	Dhir et al., 2009
<i>Mentha longifolia</i> subsp. <i>wissii</i>	Wild Mint		x		Cr	Zurayk et al., 2001
<i>Merwillia plumbea</i>	Blue Squill		x		Cd	Lux et al., 2011
* <i>Panicum repens</i>	Couch Panicum		x		Cd & Pb	Zeng et al., 2015
* <i>Phragmites australis</i>	Common Reed		x		Al, Ca, Cd, Cr, Cu, Fe, K, Mn, Ni, Pb, Si & Zn; NH ₃ , NO ₃ & PO ₄ ³⁻ ; domestic and wastewater effluent; benzene, phenanthrene; atrazine & pentachlorophenol	Kumari and Tripathi, 2015; Ranieri et al., 2016; Ye et al., 1997
<i>Potamogeton nodosus</i>	Fonteingras		x		HMX, RDX & TNT	Bhadra et al., 2001; Dietz and Schnoor, 2001
<i>Potamogeton pectinatus</i>	Fennel-leaved Pondweed		x		Cd, Cr, Cu, Mn, Ni, Pb & Zn; radionuclides	Singh et al., 2005; Dhir et al., 2009
<i>Prionium serratum</i>	Palmiet	x	x		NH ₃ , NO ₃ ⁻ , PO ₄ ³⁻ & glyphosate	Frenzel, 2018; Jacklin et al., 2020
<i>Pteridium aquilinum</i> subsp. <i>aquilinum</i>	Eagle Fern		x		Zn	Mkumbo et al., 2012
* <i>Pteris cretica</i>	Avery Fern		x		As	Zhao et al., 2002; CMLR, 2017
<i>Pteris vittata</i>	Ladder Brake		x		As, Cr, Cu, Hg, Ni, Pb & Zn	Visoottiviseth et al., 2002; Wang et al., 2002
<i>Rumohra adiantiformis</i>	Seven-weeks Fern		x		Petroleum	Tsao and Tsao, 2003; Famulari, 2011
<i>Ruppia maritima</i>	Beaked Tasselweed		x		Se	Gao et al., 2003; Peer et al., 2005
<i>Schoenoplectus corymbosus</i>	Matjiesgoed		x		Al, Fe, Mg & Mn	Schachtschneider et al., 2010; Schachtschneider et al., 2017
<i>Schoenoplectus scirpoides</i>	Steekbiesie		x		NH ₃ , NO ₃ ⁻ & PO ₄ ³⁻	Wright et al., 2017; Frenzel, 2018
<i>Senecio coronatus</i>	Sybossie		x		Al, Cu, Mn, Ni & Zn	Mesjasz-Przybyłowicz et al., 1994; Boyd et al., 2002; Boyd et al., 2008
<i>Sporobolus virginicus</i>	Brakgras		x		N	Payne et al., 2014
<i>Stenotaphrum secundatum</i>	Cape Kweek		x		N & P; PAHs & TPHs	Flathman and Lanza, 1998; McCutcheon and Schnoor, 2003; Milandri et al., 2012
<i>Strelitzia nicolai</i>	Natal Mock Banana		x		Domestic greywater effluent	Fowdar et al., 2017; Barron et al., 2019
<i>Strelitzia reginae</i>	Bird-of-Paradise		x		Domestic greywater effluent & petroleum	Tsao and Tsao, 2003; Fowdar et al., 2017
<i>Typha capensis</i>	Bulrush		x		Al, Cd, Cu, Fe, Mn, Ni, Pb, Se & Zn; fertilizer & herbicide; NH ₃ , NO ₃ ⁻ , PO ₄ ³⁻ & glyphosate; radionuclides; hydrophobic organics	Dietz and Schnoor, 2001; Schachtschneider et al., 2017
<i>Zantedeschia aethiopica</i>	Arum Lily		x		NH ₃ , NO ₃ ⁻ , PO ₄ ³⁻ & glyphosate	Milandri et al., 2012; Jacklin et al., 2020

HMX – octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine; PAHs – polycyclic aromatic hydrocarbons; PCBs – polychlorinated biphenyls; PHCs – Petroleum hydrocarbons; RDX – research demolition explosive (hexahydro-1,3,5-trinitro-1,3,5-triazine); TCE – trichloroethylene; TNT – trinitrotoluene-2-methyl-1,3,5-trinitrobenzene; TPHs – total petroleum hydrocarbons.

*Care to be taken when using in sustainable and sensitive systems, as they display aggressive properties.

resource remediation, assisted by the recommended indigenous plant list, must consider ecosystem dynamism in fluctuating biotic conditions and a changing climate. The assessment of ecosystem characteristics and plant specific invasiveness, whilst incorporating precautionary principles of plant introduction, are crucial prerequisites for effective planning, demanding a multidisciplinary approach between engineering and science (Richardson et al., 2020). It is for these reasons that the civil engineer assessing plant species inclusion in the proposed species list for phytoremediation initiatives must consult relevant specialists in environmental science, field botany, conservation ecology and soil science, prior to introducing plant species into GI. In considering the habitats and context of plant species located in the WC, this interdisciplinarity will equip the practising engineer with the necessary skills and knowledge backed by scientific literature to design an effective but sustainable phytoremediation system for runoff remediation and site rehabilitation initiatives.

CONCLUSIONS

Increased anthropogenic activities have exposed the urban and rural WC to sustained environmental degradation, posing a major environmental and human health problem (Malherbe et al., 2018). In an effort to sustainably remediate soil and water polluted by deleterious contaminants, engineered strategies of an effective and affordable nature are required. GI offers a sustainable and cost-effective solution for various environmental contaminants in soil, sediment and water (Terry and Banuelos, 1999). In combating biodiversity loss, the selection of potential plants for bioremediation initiatives must consider species that are naturally acclimatised to the recipient ecosystem, and which do not threaten the natural biodiversity. This is particularly important for urban remediation technologies as urban areas are often the initial sites for introduction, and from which invasions spread (Zengeya and Wilson, 2020). Reduced ecosystem biodiversity poses one of the greatest ecological engineering challenges (Tilman and Lehman, 2001). The need to use effective plant species for remediation cannot overshadow the need to protect and conserve the ecosystem. Thus the use of indigenous plant species that ameliorate the degraded environment and contribute to preservation must be considered. Although a specific species may not be recorded as invasive to the WC phytogeographic area, with introduction to a new habitat, the non-invasive species may threaten habitat sustainability (Richardson et al., 2020). For this reason, species sourced from similar habitat conditions must be preferred.

The listed potential phytoremediators may aid in regulating the natural ecosystem, maintain equilibrium, and increase heterogeneity. They are also capable of adjusting to dynamic biogeographic conditions of various recipient habitats. This heterogeneity between species and phytogeographic distributions creates opportunities for the introduction of distinct vegetation into the diverse habitats of the WC, capable of remediating a wide range of environmental contaminants, at a fraction of the cost of conventional techniques. The non-invasive plants offer an attractive alternative to known invasive alien plants, while supporting natural biodiversity and conservation initiatives (Pyšek and Richardson, 2010).

In selecting potential phytoremediators the dynamic factors that mediate plant species' interactions with resident biota and prevailing conditions, affecting potential invasiveness within a specific ecosystem, need to be considered. It is imperative that the practicing engineer receives input from relevant specialists, and that plant introduction is only undertaken with their satisfaction. It would be advantageous for the Water Research Commission (WRC) to work towards establishing a guideline, accounting for different pollution and ecosystem contexts, with input from the following specialists: hydrologists, town and regional planners,

disaster management practitioners, ecologists and soil scientists, environmental and municipal managers, and landscape architects, which engineers could use with less oversight.

In decontaminating sites exposed to extreme and continuous pollution, field crops potentially contribute to phytoremediation in toxic conditions due to their short life cycle, large biomass production and adaptability to the changing environment (Ciura et al., 2005), in turn, mitigating severe environmental effects and greatly reducing environmental cost (Santos-Jallath et al., 2012). This can, however, only be done with greater monitoring of pollutant toxicity tolerance and rotation over a number of cropping cycles under strict circumstances.

Acknowledging the WC's global biodiversity richness status (Von Hase et al., 2003), the absence of research relating to the phytoremediation potential of the WC plant species for GI initiatives reinforces the need for further studies. In highlighting the remediation efficacy of endemic species, the vegetation may be granted an additional economic value that could aid the decisions which encourage protection and development (Barbier et al., 1997).

ACKNOWLEDGEMENT

This research was funded by the National Research Foundation (NRF) Thuthuka Fund, with project identity: TTK180418322426.

REFERENCES

- ABHILASH PC, POWELL JR, SINGH HB and SINGH BK (2012) Plant-microbe interactions: novel applications for exploitation in multipurpose remediation technologies. *Trends Biotechnol.* **30** (8) 416–420. <https://doi.org/10.1016/j.tibtech.2012.04.004>
- ABHILASH PC (2015) Managing soil resources from pollution and degradation: the need of the hour. *J. Clean. Prod.* **102** 550–551. <https://doi.org/10.1016/j.jclepro.2015.04.046>
- ALI S, CHAUDHARY A, RIZWAN M, ANWAR HT, ADREES M, FARID M, IRSHAD MK, HAYAT T and ANJUM SA (2015) Alleviation of chromium toxicity by glycinebetaine is related to elevated antioxidant enzymes and suppressed chromium uptake and oxidative stress in wheat (*Triticum aestivum* L.). *Environ. Sci. Pollut. Res.* **22** (14) 10669–10678. <https://doi.org/10.1007/s11356-015-4193-4>
- BAKER AJM and BROOKS R (1989) Terrestrial higher plants which hyperaccumulate metallic elements. A review of their distribution, ecology and phytochemistry. *Biorecovery.* **1** (2) 81–126.
- BARBIER E, ACREMAN M and KNOWLER D (1997) *Economic Valuation of Wetlands: A Guide for Decision-makers and Planners.* Ramsar Convention Office, Gland. 155 pp.
- BARRON NJ, DELETIC A, JUNG J, FOWDAR H, CHEN Y and HATT BE (2019) Dual-mode stormwater-greywater biofilters: The impact of alternating water sources on treatment performance. *Water Res.* **159** 521–537. <https://doi.org/10.1016/j.watres.2019.04.020>
- BHADRA R, WAYMENT DG, WILLIAMS RK, BARMAN SN, STONE MB, HUGHES JB and SHANKS JV (2001) Studies on plant-mediated fate of the explosives RDX and HMX. *Chemosphere.* **44** (5) 1259–1264. [https://doi.org/10.1016/S0045-6535\(00\)00272-1](https://doi.org/10.1016/S0045-6535(00)00272-1)
- BONOMO L, PASTORELLI G & ZAMBON N (1997) Advantages and limitations of duckweed-based wastewater treatment systems. *Water Sci. Technol.* **35** (5) 239. <https://doi.org/10.2166/wst.1997.0207>
- BOYD RS, DAVIS MA, WALL MA and BALKWILL K (2002) Nickel defends the South African hyperaccumulator *Senecio coronatus* (Asteraceae) against *Helix aspersa* (Mollusca: Pulmonidae). *Chemoecology.* **12** (2) 91–97. <https://doi.org/10.1007/s00049-002-8331-3>
- BOYD RS, DAVIS MA and BALKWILL K (2008) Elemental patterns in Ni hyperaccumulating and non-hyperaccumulating ultramafic soil populations of *Senecio coronatus*. *S. Afr. J. Bot.* **74** (1) 158–162. <https://doi.org/10.1016/j.sajb.2007.08.013>
- BROOKS RR, NAIDU SM, MALAISSE F and LEE J (1986) The elemental content of metallophytes from the copper/cobalt deposits of Central Africa. In: *Bull. Soc. R. Bot. Belg.* **119** (2) 179–191.

- BUDELSKY R and GALATOWITSCH S (2004) Establishment of *Carex stricta* Lam. seedlings in experimental wetlands with implications for restoration. *Plant Ecol.* **175** (1) 91–105. <https://doi.org/10.1023/B:VEGE.0000048102.72101.50>
- CASTRO-DIEZ P, VALLE G, CONZALEZ-MUNOZ N and ALONSO A (2014) Can the life-history strategy explain the success of the exotic trees *Ailanthus altissima* and *Robinia pseudoacacia* in Iberian floodplain forests? *PLoS One.* **9** (6). <https://doi.org/10.1371/journal.pone.0100254>
- CHANEY RL, MALIK M, LI YM, BROWN SL, BREWER EP, ANGLE JS and BAKER AJ (1997) Phytoremediation of soil metals. *Curr. Opin. Biotechnol.* **8** (3) 279–284. [https://doi.org/10.1016/S0958-1669\(97\)80004-3](https://doi.org/10.1016/S0958-1669(97)80004-3)
- CHEN M, LI XM, YANG Q, ZENG GM, ZHANG Y, LIAO DX, LIU JJ, HU JM and GUO L (2008) Total concentrations and speciation of heavy metals in municipal sludge from Changsha, Zhuzhou and Xiangtan in middle-south region of China. *J. Hazardous Mater.* **160** (2–3) 324–329. <https://doi.org/10.1016/j.jhazmat.2008.03.036>
- CHOUDHARY MP, CHAUHAN GS and KUSHWAH YK (2015) Environmental degradation: causes, impacts and mitigation. In: *National Seminar on Recent Advancements in Protection of Environment and Its Management Issues*, February 2015, Rajasthan.
- CIURA J, PONIEDZIALEK M, SEKARA A and JEDRSZCZYK E (2004) The possibility of using crops as metal phytoremediants. *Pol. J. Environ. Stud.* **14** (1) 17–22.
- CMLR (Centre for Mined Land Rehabilitation) (2017) Global Hyperaccumulator Database. URL: <http://hyperaccumulators.smi.uq.edu.au/collection/> (Accessed 15 March 2020).
- CONSTANTINE M, MUSINGAFI C and TOM T (2014) Fresh water sources pollution: A human related threat to fresh water security in South Africa. *Res. Acad. Soc. Sci.* **1** (2) 72–81.
- CUNNINGHAM SD, BERTI WR and HUANG JW (1995) Phytoremediation of contaminated soils. *Trends Biotechnol.* **13** (9) 393–397.
- CUNNINGHAM SD, SHANN JR, CROWLEY DE and ANDERSON TA (1997) Phytoremediation of contaminated water and soil. In: Kruger EL, Anderson TA and Coats JR (eds.) *Phytoremediation of Soil and Water Contaminants*. ACS Symposium Series, Iowa. <https://doi.org/10.1021/bk-1997-0664.ch001>
- DE VILLIERS and THIART C (2007) The nutrient status of South African rivers: Concentrations, trends and fluxes from the 1970s to 2005. *S. Afr. J. Sci.* **103** (7–8) 343–349.
- DENG H, YE ZH and WONG MH (2004) Accumulation of lead, zinc, copper and cadmium by 12 wetland plant species thriving in metal-contaminated sites in China. *Environ. Pollut.* **132** (1) 29–40. <https://doi.org/10.1016/j.envpol.2004.03.030>
- DHIR B, SHARMILA P and SARADHI PP (2009) Potential of aquatic macrophytes for removing contaminants from the environment. *Crit. Rev. Environ. Sci. Technol.* **39** (9) 754–781. <https://doi.org/10.1080/10643380801977776>
- DIETZ AC and SCHNOOR JL (2001) Advances in phytoremediation. *Environ. Health Perspect.* **109** 163–168. <https://doi.org/10.1289/ehp.01109s1163>
- DWS (Department of Water and Sanitation, South Africa) (2018) National Water and Sanitation Master Plan (V 10.1). DWS, Pretoria.
- EL-KHATIB AA, HEGAZY AK and ABO-EL-KASSEM AM (2014) Bioaccumulation potential and physiological responses of aquatic macrophytes to Pb pollution. *Int. J. Phytoremed.* **16** (1) 29–45. <https://doi.org/10.1080/15226514.2012.751355>
- EWAS EA (1997) Effects of cadmium, nickel and lead on growth, chlorophyll content and proteins of weeds. *Biol. Plantarum.* **39** (3) 403–410. <https://doi.org/10.1023/A:1001084327343>
- FAMULARI S (2011) The Phytoremediation Plant Index. URL: <http://www.steviefamulari.net/phytoremediation/index.php> (Accessed 17 March 2020).
- FINLAYSON CM and MITCHELL DS (1982) Treatment of rural wastewaters in Australia with aquatic plants: a summary. *Der Tropenlandwirt – J. Agric. Trop. Subtrop.* **83** (2) 155–165.
- FLATHMAN PE and LANZA GR (1998) Phytoremediation: current views on an emerging green technology. *J. Soil Contam.* **7** (4) 415–432. <https://doi.org/10.1080/10588339891334438>
- FLETCHER TD, SHUSTER W, HUNT WF, ASHLEY R, BUTLER D, ARTHUR S, TROWSDALE S, BARRAUD S, SEMADENI-DAVIES A, BERTRAND-KRAJEWSKI J, MIKKELSEN PS, RIVARD G, UHL M, DAGENAIS D and VIKLANDER M (2015) SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. *Urban Water J.* **12** (7) 525–542. <https://doi.org/10.1080/1573062X.2014.916314>
- FOWDAR HS, HATT BE, BREEN P, COOK PLM and DELETIC A (2017) Designing living walls for greywater treatment. *Water Res.* **110** 218–232. <https://doi.org/10.1016/j.watres.2016.12.018>
- FRENZEL P (2018) Investigating the potential of floating wetlands in small farm dams in the Western Cape, South Africa. MSc thesis, Stellenbosch University.
- GAO S, TANJI K, PETERS D, LIN Z and TERRY N (2003) Selenium removal from irrigation drainage water flowing through constructed wetland cells with special attention to accumulation in sediments. *Water Air Soil Pollut.* **144** (1) 263–284. <https://doi.org/10.1023/A:1022915515425>
- GILIOMEE JH (2006) Conserving and increasing biodiversity in the large-scale, intensive farming systems of the Western Cape, South Africa. *S. Afr. J. Sci.* **102** 9–10.
- GLEBA D, BORISJUK NV, BORISJUK LG, KNEER R, POULEV A, SKARZHINSKAYA M, DUSHENKOV S, LOGENDRA S, GLEBA YY and RASKIN I (1999) Use of plant roots for phytoremediation and molecular farming. *Proc. Natl Acad. Sci.* **96** (11) 5973–5977. <https://doi.org/10.1073/pnas.96.11.5973>
- GROEBER S, PRZYBYAOWICZ W, EXHEVARRIA G, MONTARGES-PELLETIER E, BARNABAS A and MESJASZ-PRZYBYAOWICZ (2015) Fate of nickel and calcium in seedlings of the hyperaccumulator *Berkheya coddii* during germination. *Biol. Plantarum.* **59** (3) 560. <https://doi.org/10.1007/s10535-015-0527-9>
- GUERINOT ML and SALT DE (2001) Fortified foods and phytoremediation. Two sides of the same coin. *Plant Physiol.* **125** (1) 164. <https://doi.org/10.1104/pp.125.1.164>
- JACKLIN DM, BRINK IC and DE WAAL JH (2020) The potential use of plant species within a Renosterveld landscape for the phytoremediation of glyphosate and fertiliser. *Water SA* **46** (1) 94–103. <https://doi.org/10.17159/wsa/2020.v46.i1.7889>
- KHAN AG, KUEK C, CHAUDHRY TM, KHOO CS and HAYES WJ (2000) Role of plants, mycorrhizae and phytochelators in heavy metal contaminated land remediation. *Chemosphere.* **41** (1–2) 197–207. [https://doi.org/10.1016/S0045-6535\(99\)00412-9](https://doi.org/10.1016/S0045-6535(99)00412-9)
- KHAN AG, KHAN S, KHAN MA, QAMAR Z and WAQAS M (2015) The uptake and bioaccumulation of heavy metals by food plants, their effects on plants nutrients, and associated health risk: a review. *Environ. Sci. Pollut. Res.* **22** (18) 13772–13799. <https://doi.org/10.1007/s11356-015-4881-0>
- KONDO MC, LOW SC, HENNING J and BRANAS CC (2015) The impact of green stormwater infrastructure installation on surrounding health and safety. *Am. J. Public Health.* **105** (3) 114–121. <https://doi.org/10.2105/AJPH.2014.302314>
- KRÄMER U and CHARDONNENS A (2001) The use of transgenic plants in the bioremediation of soils contaminated with trace elements. *Appl. Microbiol. Biotechnol.* **55** (6) 661–672. <https://doi.org/10.1007/s002530100631>
- KUMARI M and TRIPATHI BD (2015) Efficiency of *Phragmites australis* and *Typha latifolia* for heavy metal removal from wastewater. *Ecotoxicol. Environ. Saf.* **112** 80–86. <https://doi.org/10.1016/j.ecoenv.2014.10.034>
- LE MAITRE DC, BLIGNAUT JN, CLULOW A, DZIKITI S, EVERSON CS, GÖRGENS AHM and GUSH MB (2020) Impacts of plant invasions on terrestrial water flows in South Africa. In: Simberloff D (ed.) *Biological Invasions in South Africa*. Springer, Cham. https://doi.org/10.1007/978-3-030-32394-3_15
- LE ROUX JJ, CLUSELLA-TRULLAS S, MOKOTJOMELA TM, MAIRAL M, RICHARDSON DM, SKEIN L, WILSON JR, WEYL OLF and GEERTS S (2020) Biotic interactions as mediators of biological invasions: insights from South Africa. In: Simberloff D (ed.) *Biological Invasions in South Africa*. Springer, Cham. https://doi.org/10.1007/978-3-030-32394-3_14
- LEGUIZAMO MAO, GOMEZ WDF and SARMIENTO MCG (2017) Native herbaceous plant species with potential use in phytoremediation of heavy metals, spotlight on wetlands — A review. *Chemosphere.* **168** 1230–1247. <https://doi.org/10.1016/j.chemosphere.2016.10.075>

- LI G, HU N, DING D, ZHENG J, LIU Y, WANG Y and NIE X (2011) Screening of plant species for phytoremediation of uranium, thorium, barium, nickel, strontium and lead contaminated soils from a uranium mill tailings repository in south China. *Bull. Environ. Contam. Toxicol.* **86** (6) 646–652. <https://doi.org/10.1007/s00128-011-0291-2>
- LUX A, VACULÍK M, MARTINKA M, LIŠKOVÁ D, KULKARNI MG, STIRK WA and VAN STADEN J (2011) Cadmium induces hypodermal periderm formation in the roots of the monocotyledonous medicinal plant *Merwillia plumbea*. *Ann. Bot.* **107** (2) 285–292. <https://doi.org/10.1093/aob/mcq240>
- MACEK T, MACKOVÁ M and KÁŠ J (2000) Exploitation of plants for the removal of organics in environmental remediation. *Biotechnol. Adv.* **18** (1) 23–34. [https://doi.org/10.1016/S0734-9750\(99\)00034-8](https://doi.org/10.1016/S0734-9750(99)00034-8)
- MALAN M, MÜLLER F, CYSTER L, RAITT L and AALBERS J (2015) Heavy metals in the irrigation water, soils and vegetables in the Philippi horticultural area in the Western Cape Province of South Africa. *Environ. Monit. Assess.* **187** (1) 1–8. <https://doi.org/10.1007/s10661-014-4085-y>
- MALHERBE H, GEBEL M, PAULEIT S and LORZ C (2018) Land use pollution potential of water sources along the southern coast of South Africa. *Change Adaptation Socio-Ecol. Syst.* **4** (1) 7–20. <https://doi.org/10.1515/cass-2018-0002>
- MARRUGO-NEGRETE J, DURANGO-HERNÁNDEZ J, PINEDO-HERNÁNDEZ J, OLIVERA-VERBEL J and DIETZ S (2015) Phytoremediation of mercury-contaminated soils by *Jatropha curcas*. *Chemosphere.* **127** 58–63. <https://doi.org/10.1016/j.chemosphere.2014.12.073>
- MCCUTCHEON S and SCHNOOR J (2003) Overview of phytotransformation and control of wastes. In: Schnoor J (ed.) *Phytoremediation: Transformation and Control of Contaminants*. John Wiley and Sons, Ltd., New Jersey.
- MCDOWELL C and MOLL E (1992) The influence of agriculture on the decline of west coast renosterveld, south-western Cape, South Africa. *J. Environ. Manage.* **35** (3) 173–192. [https://doi.org/10.1016/S0301-4797\(05\)80118-5](https://doi.org/10.1016/S0301-4797(05)80118-5)
- MEAGHER RB (2000) Phytoremediation of toxic elemental and organic pollutants. *Curr. Opin. Plant Biol.* **3** (2) 153–162. [https://doi.org/10.1016/S1369-5266\(99\)00054-0](https://doi.org/10.1016/S1369-5266(99)00054-0)
- MESJASZ-PRZYBYLOWICZ J, BALKWILL K, PRZYBYLOWICZ WJ and ANNEGARN HJ (1994) Proton microprobe and X-ray fluorescence investigations of nickel distribution in serpentine flora from South Africa. *Nuclear Inst. Meth. Phys. Res.* **89** (1–4) 208–212. [https://doi.org/10.1016/0168-583X\(94\)95174-8](https://doi.org/10.1016/0168-583X(94)95174-8)
- MILANDRI M, WINTER KJ, CHIMPANGO SBM, ARMITAGE NP, MBUIDN, JACKSON GE and LIEBAU V (2012) The performance of plant species in removing nutrients from stormwater in biofiltration systems in Cape Town. *Water SA.* **38** (5) 275–662. <https://doi.org/10.4314/wsa.v38i5.2>
- MKANDAWIRE M and DUDEL EG (2005) Accumulation of arsenic in *Lemna gibba* L. (duckweed) in tailing waters of two abandoned uranium mining sites in Saxony, Germany. *Sci. Total Environ.* **336** (1–3) 81–89. <https://doi.org/10.1016/j.scitotenv.2004.06.002>
- MKUMBO S, MWEGOHA W and RENMAN G (2012) Assessment of the phytoremediation potential for Pb, Zn and Cu of indigenous plants growing in a gold mining area in Tanzania. *Int. J. Environ. Sci.* **2** (4) 2425–2434.
- MÜLLER FL, JOUBERT ME, CYSTER LF and RAITT LM (2014) Heavy metal retention by soils and the subsequent uptake thereof by Cripps Pink/M7 apple trees under organic and chemical fertilizer applications. *Photon. Int. J. Agric.* **125** 340–346.
- MUSINGAFI CM and TOM T (2014) Fresh Water Sources Pollution: A Human Related Threat To Fresh Water Security in South Africa. *J. Public Polic. Gov.* **1** (2) 72–81.
- NEL JL, LE MAITRE DC, NEL DC, REYERS B, ARCHIBALD S, VAN WILGEN BW, FORSYTH GG, THERON AK, O'FARRELL PJ, KAHINDA JMM and co-authors (2014) Natural hazards in a changing world: a case for ecosystem-based management. *PLoS One.* **9** (5) 1–12. <https://doi.org/10.1371/journal.pone.0095942>
- NOMQUPHU W, BRAUNE E and MITCHELL S (2007) The changing water resources monitoring environment in South Africa. *S. Afr. J. Sci.* **103** (7–8) 306–310.
- OBERHOLSTER PJ and ASHTON PJ (2008) State of the nation report: An overview of the current status of water quality and eutrophication in South African rivers and reservoirs. CSIR, Pretoria.
- PAKDEL P and PEIGHAMBARDOUST S (2018) A review on acrylic based hydrogels and their applications in wastewater treatment. *J. Environ. Manage.* **217** 123–143. <https://doi.org/10.1016/j.jenvman.2018.03.076>
- PAYNE EGI, HATT BE, DELETIC A, DOBBIE MF, MCCARTHY DT and CHANDRASENA GI (2015) Adoption guidelines for stormwater biofiltration systems – Summary report. Cooperative Research Centre for Water Sensitive Cities, Melbourne.
- PAYNE EGI, PHAM T, COOK PLM, FLETCHER TD, HATT BE and DELETIC A (2014) Biofilter design for effective nitrogen removal from stormwater—influence of plant species, inflow hydrology and use of a saturated zone. *Water Sci. Technol.* **69** (6) 1312–1319. <https://doi.org/10.2166/wst.2014.013>
- PEER WA, BAXTER IR, RICHARDS EL, FREEMAN JL and MURPHY AS (2005) Phytoremediation and hyperaccumulator plants. In: Tamas MJ and Martinoia E (eds) *Molecular Biology of Metal Homeostasis and Detoxification*. Springer, Berlin. 299–340. https://doi.org/10.1007/4735_100
- PEUKE AD and RENNENBERG H (2005) Phytoremediation with transgenic trees. *J. Biosci.* **60** (3–4) 199–207.
- PEUKE AD and RENNENBERG H (2006) Heavy metal resistance and phytoremediation with transgenic trees. In: Fladung M and Ewald D (eds.) *Tree Transgenesis*. 137–155. Springer, Berlin. https://doi.org/10.1007/3-540-32199-3_7
- PILON-SMITS E (2005) Phytoremediation. *Annual Review of Plant Bioogy.* **56** 15–39. <https://doi.org/10.1146/annurev.arplant.56.032604.142414>
- POONAM, BHARDWAJ R, SHARMA R, HANDA N, KAUR H, KAUR R, SIRHINDI G and THUKRAL AK (2014) Prospects of field crops for phytoremediation of contaminants. In: Ahmad P and Rasool S (eds.) *Emerging Technologies and Management of Crop Stress Tolerance*. Elsevier, Amsterdam. <https://doi.org/10.1016/B978-0-12-800875-1.00019-3>
- PRZYBYLOWICZ WJ, PINEDA CA, RAMA DBK and MESJASZ-PRZYBYLOWICZ J (2001) Elemental distribution in *Senecio anomalochrous*, a Ni hyperaccumulator from South Africa. *S. Afr. J. Sci.* **97** (11) 593–595.
- PYŠEK P (1995) On the terminology used in plant invasion studies. In: Pyšek P, Prach K, Rejmánek M and Wade M (eds.) *Plant Invasions: General Aspects and Special Problems*. SPB Academic Publishing, Amsterdam. 71–81.
- PYŠEK P and RICHARDSON DM (2010) Invasive species, environmental change and management, and health. *Annu. Rev. Environ. Resour.* **35** 25–55. <https://doi.org/10.1146/annurev-environ-033009-095548>
- RADA EC, ANDREOTTOLA G, ISTRATE IA, VIOTTI P, CONTI F and MAGARIL ER (2019) Remediation of soil polluted by organic compounds through chemical oxidation and phytoremediation combined with DCT. *Int. J. Environ. Res. Public Health.* **16** (17) 3179. <https://doi.org/10.3390/ijerph16173179>
- RANIERIE, FRATINO U, PETRELLA A, TORRETTA V and RADA EC (2016) *Ailanthus Altissima* and *Phragmites Australis* for chromium removal from a contaminated soil. *Environ. Sci. Pollut. Res.* **23** (16) 15983–15989. <https://doi.org/10.1007/s11356-016-6804-0>
- RASKIN I, KUMAR PN, DUSHENKOV S and SALT DE (1994) Bioconcentration of heavy metals by plants. *Curr. Opin. Biotechnol.* **5** (3) 285–290. [https://doi.org/10.1016/0958-1669\(94\)90030-2](https://doi.org/10.1016/0958-1669(94)90030-2)
- READ J, WEVILL T, FLETCHER TD and DELETIC A (2008) Variation among plant species in pollutant removal from stormwater in biofiltration systems. *Water Res.* **42** (4–5) 893–902. <https://doi.org/10.1016/j.watres.2007.08.036>
- READ J, FLETCHER TD, WEVILL T and DELETIC A (2010) Plant traits that enhance pollutant removal from stormwater in biofiltration systems. *Int. J. Phytoremed.* **12** (1) 34–53. <https://doi.org/10.1080/15226510902767114>
- RICHARDSON DM, FOXCROFT LC, LATOMBE G, LE MAITRE DC, ROUGET M and WILSON JR (2020) The biogeography of South African terrestrial plant invasions. In: Van Wilgen B, Measey J, Richardson DM, Wilson JR and Zengeya TA (eds.) *Biological Invasions in South Africa*. Springer, Cham.

- RIZWAN M, ALI S, RIZVI H, RINKLEBE J, TSANG DCW, MEERS E, OK YS and ISHAQUE W (2016) Phytomanagement of heavy metals in contaminated soils using sunflower: a review. *Crit. Rev. Environ. Sci. Technol.* **46** (18) 1498–1528. <https://doi.org/10.1080/10643389.2016.1248199>
- SALT DE, SMITH RD and RASKIN I (1998) Phytoremediation. *Annu. Rev. Plant Physiol. Plant Mol. Biol.* **49** (1) 643–668. <https://doi.org/10.1146/annurev.arplant.49.1.643>
- SALT DE, BLAYLOCK M, KUMAR NPBA, DUSHENKOV V, ENSLEY BD, CHET I and RASKIN I (1995) Phytoremediation: a novel strategy for the removal of toxic metals from the environment using plants. *Biotechnology*. **13** (5) 468–474. <https://doi.org/10.1038/nbt0595-468>
- SANTOS-JALLATH J, CASTRO-RODRÍGUEZ A, HUEZO-CASILLAS J and TORRES-BUSTILLOS L (2012) Arsenic and heavy metals in native plants at tailings impoundments in Queretaro, Mexico. *Phys. Chem. Earth A/B/C.* **37** 10–17. <https://doi.org/10.1016/j.pce.2011.12.002>
- SCHACHTSCHNEIDER K, MUASYA M and SOMERSET V (2010) Are indigenous sedges useful for phytoremediation and wetland rehabilitation? CSIR Report No. NE04-PO, CSIR, Pretoria.
- SCHACHTSCHNEIDER K, CHAMIER J and SOMERSET V (2017) Phytostabilization of metals by indigenous riparian vegetation. *Water SA.* **43** (2) 177. <https://doi.org/10.4314/wsa.v43i2.01>
- SCHLOEMANN H (1995) The geochemistry of some common Western Cape soils (South Africa) with emphasis on toxic and essential elements. PhD dissertation, University of Cape Town.
- SIBANDA T, SELVARAJAN R and TEKERE M (2015) Urban effluent discharges as causes of public and environmental health concerns in South Africa's aquatic milieu. *Environ. Sci. Pollut. Res.* **22** (23) 18301–18317. <https://doi.org/10.1007/s11356-015-5416-4>
- SINGH NK, PANDEY GC, RAI UN, TRIPATHI RD, SINGH HB and GUPTA DK (2005) Metal accumulation and ecophysiological effects of distillery effluent on *Potamogeton pectinatus* L. *Bull. Environ. Contam. Toxicol.* **74** (5) 857–863. <https://doi.org/10.1007/s00128-005-0660-9>
- TERRY N and BAÑUELOS GS (1999) *Phytoremediation of Contaminated Soil and Water*. CRC Press, Boca Raton. <https://doi.org/10.1201/9781439822654>
- TILMAN D and LEHMAN C (2001) Human-caused environmental change: Impacts on plant diversity and evolution. *Proc. Natl Acad. Sci. United States Am.* **98** (10) 5433. <https://doi.org/10.1073/pnas.091093198>
- TRIPATHI V, FRACETO LF and ABHILASH PC (2015) Sustainable clean-up technologies for soils contaminated with multiple pollutants: plant-microbe-pollutant and climate nexus. *Ecol. Eng.* **82** 330–335. <https://doi.org/10.1016/j.ecoleng.2015.05.027>
- TSAO K and TSAO D (2003) Analysis of phytoscapes Species for BP Retail Sites, BP Group Environmental Management Company. Report published as Capstone Project paper to Benedictine University, Lile.
- VAN WILGEN BW, RICHARDSON DM, LE MAITRE DC MARAIS C and MAGADLELA D (2001) The economic consequences of alien plant invasions: examples of impacts and approaches to sustainable management in South Africa. *Environ. Dev. Sustainability.* **3** (2) 145–168. <https://doi.org/10.1023/A:1011668417953>
- VAN WILGEN BW, WILSON JR, WANNENBURGH A and FOXCROFT LC (2020) The extent and effectiveness of alien plant control projects in South Africa. In: Van Wilgen B, Measey J, Richardson DM, Wilson JR and Zengeya TA (eds). *Biological Invasions in South Africa*. Springer, Cham.
- VAMERALI T, BANDIERA M and MOSCA G (2010) Field crops for phytoremediation of metal-contaminated land, A review. *Environ. Chem. Lett.* **8** (1) 1–17. <https://doi.org/10.1007/s10311-009-0268-0>
- VARDANYAN LG and INGOLE BS (2006) Studies on heavy metal accumulation in aquatic macrophytes from Sevan (Armenia) and Carambolim (India) lake systems. *Environ. Int.* **32** (2) 208–218. <https://doi.org/10.1016/j.envint.2005.08.013>
- VINEYARD D, INGWERSEN WW, HAWKINS TR, XUE X, DEMEKE B and SHUSTER W (2015) Comparing green and grey infrastructure using life cycle cost and environmental impact: A rain garden case study in Cincinnati, OH. *J. Am. Water Resour. Assoc.* **52** (5) 1342–1360. <https://doi.org/10.1111/1752-1688.12320>
- VISOOTTIVISETH P, FRANCESCONI K and SRIDOKCHAN W (2002) The potential of Thai indigenous plant species for the phytoremediation of arsenic contaminated land. *Environ. Pollut.* **118** (3) 453–461. [https://doi.org/10.1016/S0269-7491\(01\)00293-7](https://doi.org/10.1016/S0269-7491(01)00293-7)
- VON HASE A, ROUGET M, MAZE K and HELME N (2003) A finescale conservation plan for Cape lowlands Renosterveld: technical report. Report no CCU 2/03. Cape Conservation Unit, Botanical Society of South Africa, Claremont.
- WANG J, ZHAO FJ, MEHARG AA, RAAB A, FELDMANN J and MCGRATH SP (2002) Mechanisms of arsenic hyperaccumulation in *Pteris vittata*. Uptake kinetics, interactions with phosphate, and arsenic speciation. *Plant Physiol.* **130** (3) 1552–1561. <https://doi.org/10.1104/pp.008185>
- WOLVERTON BC and WOLVERTON JD (1993) Plants and soil microorganisms: removal of formaldehyde, xylene, and ammonia from the indoor environment. *J. Mississippi Acad. Sci.* **38** (2) 11–15.
- WOLVERTON BC and WOLVERTON JD (1996) Interior plants: their influence on airborne microbes inside energy-efficient buildings. *J. Mississippi Acad. Sci.* **41** (2) 99–105.
- WRIGHT D, PURNELL A, ALTERN S and FRENZEL P (2017) Floating wetlands – increasing biodiversity and cleaning water in farm dams. Table Mountain Fund, Cape Town.
- YANG F, YANG Y, LI H and CAO M (2015) Removal efficiencies of vegetation-specific filter strips on nonpoint source pollutants. *Ecol. Eng.* **82** 145. <https://doi.org/10.1016/j.ecoleng.2015.04.018>
- YE ZH, BAKER AJM, WONG MH and WILLIS AJ (1997) Zinc, lead and cadmium tolerance, uptake and accumulation by the common reed, *Phragmites australis* (Cav.) Trin. ex Steudel. *Ann. Bot.* **80** (3) 363–370. <https://doi.org/10.1006/anbo.1997.0456>
- ZENG Z, GAO G, YANG J, YUAN J and YANG Z (2015) The integrated response of torpedograss (*Panicum repens*) to Cd–Pb co-exposures. *Ecol. Eng.* **82** 428–431. <https://doi.org/10.1016/j.ecoleng.2015.05.001>
- ZENGEYA TA and WILSON JR (2020) The status of biological invasions and their management in South Africa in 2019. (Second order draft). South African National Biodiversity Institute, Kirstenbosch and DSI-NRF Centre of Excellence for Invasion Biology, Stellenbosch.
- ZHANG XH, LIU J, HUANG HT, CHEN J, ZHU YN and WANG DQ (2007) Chromium accumulation by the hyperaccumulator plant *Leersia hexandra* Swartz. *Chemosphere.* **67** (6) 1138–1143. <https://doi.org/10.1016/j.chemosphere.2006.11.014>
- ZHAO FJ, DUNHAM SJ and MCGRATH SP (2002) Arsenic hyperaccumulation by different fern species. *New Phytol.* **156** (1) 27–31. <https://doi.org/10.1046/j.1469-8137.2002.00493.x>
- ZURAYK R, SUKKARIYAH B and BAALBAKI R (2001) Common hydrophytes as bioindicators of nickel, chromium and cadmium pollution. *Water Air Soil Pollut.* **127** (1–4) 373–388. <https://doi.org/10.1023/A:1005209823111>