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VIEW POINT

Sustainability of crop production from polluted lands

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Abstract Sustainable food production for a rapidly growing global population is a major challenge of this century. In order to meet the demand for food production, an additional land area of 2.7–4.9 Mha year^{-1} will be required for agriculture. However, one-third of arable lands are already contaminated; therefore, the use of polluted lands will have to feature highly in modern agriculture. The use of such lands comes, however, with additional challenges, and suitable agrotechnological interventions are essential for ensuring the safety and sustainability of relevant production system. There are also other issues to consider, such as cost–benefit analysis, the possible entry of pollutants into the phytoproducts, certification and marketing of such products, in order to achieve the large-scale exploitation of polluted lands. The present article addresses the sustainability challenges of crop production from polluted lands and briefly outlines the plausible strategies for using polluted lands for sustainable agricultural extensification.

Keywords Polluted lands · Crop production · Sustainability · Agricultural extensification · Bioeconomy · Phytoproducts

1 Increasing crop production for a growing population: the need of the hour

The population of the Earth is expected to reach ~9.5 billion people by the mid-twenty-first century (Godfray et al. 2010). Such an explosive rise in population will create the demand for a 70 % increase in food, feed and fiber production (Montanarella and Vargas 2012). Perhaps one of the greatest challenges is to increase the food production for a rapidly growing population in a sustainable manner (Foley et al. 2011). However, land is a limited resource and agricultural use of land will be in competition with land use for habitation, infrastructure and industry. Any modifications to the existing patterns of land use will affect the resilience of ecological and socioeconomic systems (Anderson 2010). Therefore, the dilemma is to increase the crop production without a significant increase in the use of arable land (Godfray and Garnett 2014). Accomplishing these goals will become increasingly difficult under changing climatic conditions and the resulting effects on crop growth, yield and disease susceptibility. The changing climate may also influence the nutritional quality of crops (Myers et al. 2014). There is a pressing need to develop suitable strategies for increasing global food production without any additional social, economic or ecological pressures (Rockström et al. 2009; Lambin and Meyfrodt 2011; Dubey et al. 2016).

One strategy to address these problems has been to leverage ‘omic technologies’ to engineer genetically modified (GM) crops with enhanced productivity, nutritional quality and/or stress tolerance. A significant drawback to this approach is the growing public resistance to GM crops (Ronald 2011), based principally on concerns about their perceived safety, the lack of scientific information on the long-term effects of GM crop consumption and the ethical considerations associated with genetic modification (Gilbert 2013). Intensifying traditional agricultural practices has been suggested as an immediate strategy for increasing the global food supply, but the excessive use of agrochemicals during the last few decades has already resulted in the severe

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pollution of biosphere (Abhilash et al. 2013a, b; Popp et al. 2013). Hence, ~25 % of global land resources are highly degraded and ~44 % are moderately degraded with the level of contamination is steadily increasing. Another strategy that could be used to meet global food demands would involve the safe and productive use of polluted lands to provide an additional avenue for agricultural extensification. There are a number of challenges associated with this approach, including the possible entry of pollutants into the phytoproducts. The present article examines the sustainability of crop production on polluted lands and provides potential strategies for converting polluted lands to an agricultural landscape to foster a bioeconomy (Jacobsen et al. 2013) for sustainable development.

2 Crop production on polluted lands: an environmental point of view

Land is a critical resource as it supports local food webs and contributes to global biogeochemical cycles. Land resources also provide agricultural production and support numerous other human needs and services. The terrestrial environment is also a primary sink for pollutants (Banwart 2011). The growing population exerts tremendous pressure on land for food, feed, fiber and biofuel production. It is estimated that an additional 2.7–4.9 Mha $year^{-1}$ will be required to meet the food demand of growing populations (Lambin and Meyfrodt 2011). The agricultural extensification of new landscapes at the cost of existing forests, wetlands and grasslands is not a sustainable option as it accelerates the biodiversity loss and other environmental issues (Garnett et al. 2013). However, by adopting prudent scientific and technological interventions, polluted lands could be utilized safely for agricultural production (Lambin and Meyfrodt 2011). Polluted lands are generally perceived as a potential threat to human health and food safety, but the demand for arable lands will inevitably require that these lands be considered as an untapped resource for environmental and agricultural sustainability (Abhilash et al. 2013a, b; Weyens et al. 2009). Using polluted lands for agriculture will not only address the increased food demand of growing populations but will also restore those degraded lands to productive use rather leaving them dormant and unused. There is also the potential to couple agricultural production on polluted lands with the cultivation of biomass and biofuel crops to meet growing energy demand (Weyens et al. 2009) and with biofortification efforts to improve the nutrient content of agricultural products (Zhao and McGrath 2009). Nevertheless, there are several ecotoxicological, economic and social considerations associated with crop production on polluted lands that must be thoroughly addressed (Tripathi et al. 2014a). The following sections provide (1) a state of the art of crop productions from polluted lands and (2) strategies for simultaneously minimizing the potential risk to human receptors while converting crop production on polluted lands into a sustainable enterprise.

3 Polluted lands for edible crop production and biofortification

A selected list of crop plants being tested under field and controlled conditions is provided in Table 1. The uptake and accumulation of pollutants in crops vary with species or cultivars, the type of pollutants and level of contamination (Khan et al. 2010; Ismail et al. 2014). For instance, a field trial on a moderately Cd-contaminated (0.69–0.96 mg kg^{-1}) site in China based on a rotation system of rape (*Brassica napus* L.) seed to rice (*Oryza sativa* L.) restricted the phytoaccumulation of Cd in rice. The rape seed cultivar Zhucang Huzai accumulated a high Cd concentration (>0.2 mg kg^{-1}), whereas the Cd concentration in cultivar Chuanyou II-93 was well below the limit as given in Table 1. Similarly, Cd concentrations of the brown rice were below the permissible limits (Yu et al. 2014). The concentrations of As, Cu, Co, Pb and Zn in cassava (*Manihot esculenta* Crantz) growing on the contaminated soils of the Zambian copper belt were reported by Kríbek et al. (2014). Interestingly, the level of Cu in leaves and tubers of cassava grown in strongly contaminated areas do not exceed the daily maximum tolerance limit for dietary intake (0.5 mg kg^{-1} body weight). However, the highest tolerable weekly ingestion of Pb and As exceeded the relevant dietary limits in the vicinity of smelters.

Warren et al. (2003) conducted a detailed field trial to assess the uptake of As by beet (*Beta vulgaris* L.), calabrese vegetables like cauliflower (*Brassica oleracea* var botrytus), lettuce (*Lactuca sativa* L.), potato (*Solanum tuberosum* L.), radish (*Raphanus sativus* L) and spinach (*Spinacia oleracea* L.) growing on As-contaminated soil (748 mg kg^{-1}) near an As smelter in Cornwall, UK. This soil had been amended with ferrous sulfate and lime in an effort to remediate the soils through precipitation of Fe oxides in the contaminated soil. In all field trials except for spinach, ferrous sulfate addition significantly reduced the As translocation to edible parts. Moreover, the application of 0.2 % Fe oxides to soil surface (0–10 cm) reduced the As uptake by 22 %, whereas the application of 0.5 % Fe oxides reduced the As availability by 32 % (Warren et al. 2003). Madejón et al. (2011) employed traditional agricultural practices in a heavily contaminated soil in Southern Spain to limit the accumulation of As, Cu, Pb and Zn in onion (*Allium cepa* L.), lettuce, chard (*B. vulgaris* L.), potato and lemon (*Citrus limon* L. Burm.f.). The metal concentration was low in crops when the

Table 1 An indicative list of trials conducted for crop production from contaminated lands and the level of accumulation in edible parts

Crops types	Pollutant level (mg kg^{-1})	Plant parts	Type of study	FAO/WHO standards (mg kg^{-1})	Refs.
Cereals					
Barley (*Hordeum vulgare* L.)	Se (0.17)	Grains	Field	Not available	Ilbas et al. (2012)
Maize (*Zea mays* L.)	Cd (0.07), Pb (0.10), Zn (0.73)	Grains	Field	Cd (0.2), Pb (0.3), Zn (100)	Meers et al. (2010)
Rice (*Oryza sativa* L.)	Zn (22.8–23.8), Cd (0.1)	Grains	Greenhouse	Zn (100), Cd (0.2)	Weyens et al. (2009), Yu et al. (2014)
Sorghum (*Sorghum biocolor* L.)	Cu (96.2), Zn (80.9)	Leaves, roots	Field	Cu (500), Zn (100)	Zhuang et al. (2009)
Oil seeds					
Rapeseed (*Brassica napus* L.)	Cd (0.2)	Whole plant	Field	Cd (0.2)	Yu et al. (2014)
Indian mustard (*Brassica juncea* L.)	Ni (38)	Whole plant	Field	Ni (67)	Bauddh and Singh (2012)
Vegetables/fruits					
Beetroot (*Beta vulgaris* L.)	As (<0.08)	Tubers	Field	As (0.1)	Warren et al. (2003)
Bitter gourd (*Momordica charantia* L.)	Pb (0.3)	Fruit	Field	Pb (0.3)	Ismail et al. (2014)
Carrot (*Daucus carota* L.)	Ni (0.73)	Roots	Pot	Ni (67)	Stasinos and Zabetakis (2013)
Cassava (*Manihot esculenta* Crantz)	As (0.1), Co (<0.5), Cu (1.7), Zn (11)	Peeled tubers	Field	As (0.1), Co (50), Cu (500), Pb (0.3), Zn (100)	Kříbek et al. (2014)
Cauliflower (*Brassica oleracea* var. botrytis)	Cu (1.86)	Shoots	Field	Cu (500)	Ismail et al. (2014)
Lettuce (*Lactuca sativa* L.)	As (0.08)	Shoots	Field	As (0.1)	Warren et al. (2003)
Onion (*Allium cepa* L.)	Ni (1.78)	Shoots	Pot	Ni (67)	Stasinos and Zabetakis (2013)
Pineapple (*Ananas comosus* (L.) Merr.)	Marginal or degraded lands (NA)	Fruits	Field	NA	Borland et al. (2009)
Potato (*Solanum tuberosum* L.)	As (0.08), Ni (0.32)	Tubers	Field and pot	As (0.1), Ni (67)	Warren et al. (2003), Stasinos and Zabetakis (2013)
Radish (*Raphanus sativus* L.)	Zn (47.94)	Pods	Field	Zn (100)	Ismail et al. (2014)
Spinach (*Spinacia oleracea* L.)	Cd (0.05), Co (0.36), Ni (2.03), Fe (202.66), Mn (6.23), As (<0.08)	Shoots	Field	Cd (0.2), Co (50), Ni (67), Fe (425), Mn (73), As (0.1)	Ismail et al. (2014), Warren et al. (2003)
Ornamentals					
Chrysanthemum (*Chrysanthemum indicum* L. and *C. maximum* (DC.) Parsa)	Cd (7.4), Cu (7.3–8.5), Zn (≃ 130), Ni (≃ 214), Pb (≃ 110)	Cd (shoots), Cu (flowers), Zn (whole plant), Ni (whole plant), Pb (whole plant)	Field and pot	NA	Lal et al. (2008), González-Chávez and Carrillo-González (2013)
Cock's comb (*Celosia cristata* L.)	Cr (≃ 159.5), Mn (≃ 145), Fe (≃ 8000), Cu (≃ 79.5), Zn (≃ 1010), Pb (≃ 159)	Whole plant	Field	NA	Chatterjee and Singh (2012)

Table 1 continued

Crops types	Pollutant level (mg kg^{-1})	Plant parts	Type of study	FAO/WHO standards (mg kg^{-1})	Refs.
Gladiolus (*Gladiolus grandiflorus* Andrews)	Cd (8.0)	Shoots	Field	NA	Lal et al. (2008)
Marigold (*Tagetes erecta* L.)	Cd (7.0), Cu ($\simeq$310)	Cd (Shoots), Cu (whole plant)	Field	NA	Lal et al. (2008), Castillo et al. (2011)
Marigold (*Tagetes patula* L.)	Cr (15.8), Cu (22), Zn (163), Pb (43)	Cr (roots), Cu (flower), Zn (stem), Pb (roots)	Field	NA	Chatterjee and Singh (2012)
Sunflower (*Helianthus annuus* L.)	Cr (56), Mn (71), Cu (48), Zn (469), Pb (47.9)	Roots	Field	NA	Chatterjee and Singh (2012)
Biomass/bioenergy					
Castor (*Ricinus communis* L.)	Cd (0.37, 0.43), DDT (1.22, 2.27), Fe ($\simeq$280), Zn ($\simeq$65), Cr ($\simeq$50), Pb ($\simeq$30), Ni ($\simeq$12), and As ($\simeq$0.045)	Cd (leaf, stem), DDT (leaf, stem), Fe, Zn, Cr, Pb, Ni, As (whole plant)	Field	NA	Huang et al. (2011), Irshad et al. (2014)
Common reed (*Phragmites australis* (Cav.) Steud.)	Cd (<0.2), Cr (0.23), Cu (3.72), Mn (28.65), Pb (5.27), Zn (16.52)	Shoots	Field	NA	Bonanno et al. (2013)
Maize (*Zea mays* L.)	Cd (0.89), Zn (211)	Whole plant	Field	NA	Ruttens et al. (2011)
Mesquite (*Prosopis juliflora* (Sw.) DC.)	As (0.14), Cd (0.17), Cr (0.02), Cu (11.8), Mn (117), Pb (2.88), Zn (73.4)	Whole plant	Field	NA	Solís-Domínguez et al. (2011)
Physic Nut (*Jatropha curcas* L.)	As (0.06), Cr (1.26), Mn, Zn (6.5)	As, Cr, Zn (stem)	Greenhouse	NA	Juwarkar et al. (2008)
Pongam (*Pongamia glabra* Vent.)	Cr (106), Mn (71.8), Fe (908), Co (19.1), Ni (39.4), Cu (37), Zn (469), Pb (25.26)	Leaves	Field	NA	Ravikumar et al. (2013)
Prickly acacia (*Acacia nilotica* Delile)	Fe ($\simeq$240), Zn ($\simeq$175), Cr ($\simeq$150), Pb ($\simeq$105), Ni ($\simeq$20), Cd ($\simeq$9), As ($\simeq$0.045)	Whole plant	Field	NA	Irshad et al. (2014)
Rush wheatgrass (*Elymus elongatus* subsp. ponticus cv. Szarvasi-1)	Zn (300), Pb (1.35)	Zn (shoot), Pb (root)	Pot	NA	Sipos et al. (2013)
Ryegrass (*Lolium perenne* L.)	Zn ($\simeq$210), As ($\simeq$1.8), Cd ($\simeq$1.2), Pb ($\simeq$30)	Roots and shoots	Pot	NA	Guo et al. (2014)
Sorghum (*Sorghum biocolor* L.)	Pb (2.31), Zn (80.9), Cd (96.2), Cu (96.2)	Pb, Zn (leaves), Cd (roots), Cu (shoots)	Field	NA	Zhuang et al. (2009)
Soybean (*Glycine max* (L.) *Merr.*)	Cd (6.2, 11.5)	Shoots, roots	Greenhouse	NA	Murakami et al. (2007)
Yellow lupin (*Lupinus luteus* L.)	As (<1.5), Cu (21.5), Cd (1.6), Pb (3.5), Zn (472)	Shoots	Field	NA	Dary et al. (2010)

soils were limed annually and with animal manure application (Madejón et al. 2011). In all cases except for Zn and Pb, the accumulation of metals was below the regulatory limits. The heavy metal concentrations in vegetables growing on a contaminated fluvial deposit of Gilgit, Pakistan (Khan et al. 2010), were 0.24–2.1 mg Cd kg^{-1}, 15–44 mg Pb kg^{-1} and 40–247 mg Zn kg^{-1}, values generally above the regulatory limit.

Biofortification of edible plants is another avenue that could be achieved through cropping on soil polluted with contaminants that are essential micronutrients (e.g., Fe, Zn, Cu Mg and Se) (Zhu et al. 2009; Vamerali et al. 2014). Selenium is an important dietary micronutrient required for animals and beneficial for plants (Madejón et al. 2011). Selenomethionine (SeMet) is the major chemical species of Se in several grains like barley (*Hordeum vulgare* L.), wheat

(*Triticum aestivum* L.) and rye (*Secale cereale* L.) contributing to about 60–80 % of the total Se content (Stadlober et al. 2001). X-ray absorption near edge spectroscopic analysis of a rice sample obtained from a Se-contaminated region of Enshi district in south-central China revealed that Se in rice can be found predominantly as selenomethylcysteine (SeMeSeCys) in addition to SeMet (Williams et al. 2009). Selenomethylcysteine is believed to have anti-carcinogenic properties. Moreover, both SeMeSeCys and SeMet provide supplementary health benefits over inorganic Se (Rayman 2008; Rayman et al. 2008). Normally, the Se levels in the rice were reported to have 33–50 % (Beilstein et al. 1991). Since soils contaminated with Se are reported worldwide, these soils could be used for cropping Se-accumulating crops for biofortification. Selenium can also lower the uptake of Pb in rice, thereby lowering the accumulation of Pb in grains (Yu et al. 2014). Hence, cropping on Se-contaminated soils might also reduce the uptake of other pollutants as well. Linseed (*Linum usitatissimum* L.) growing on contaminated soils with elevated concentrations of Fe, Cu and Zn displayed enhanced height and number of capsules per plant (Rastogi et al. 2014). Since these metals are also essential micronutrients, cultivating linseed on metal-contaminated soil could enhance nutrient density in seeds. Vamerali et al. (2014) studied the biofortification and remediation potential of radish and maize (*Zea mays* L.) cultivated in a pyrite waste dump at Torviscosa (Udine), Italy. Although the accumulation of various heavy metals in maize grains (in mg kg^{-1}) such as Cd (<0.001), Co (<0.002), Cr (0.12), Cu (3.28), Mn (6.17), Ni (0.41), Pb (<0.001) and Zn (40.2) was found to be lower, the concentrations of Cd (2.34) and Pb (4.20) in radish were higher than the permissible limit set by the European Union. There are additional studies reporting that the accumulation of toxic metals in edible parts of plants growing on polluted soils falls within the regulatory limits. For example, the Cd, Pb and Zn accumulation in maize grain (Meers et al. 2010), As accumulation in beet root and lettuce (Warren et al. 2003) and the Ni concentration in carrot and onion (Stasinos and Zabetakis 2013) were below the limit. The above cases demonstrate that crop production on contaminated lands is being widely investigated (Figs. 1, 2) and that cultivation of crops on polluted soils does not immediately result in edible tissues with pollutant concentrations that exceed regulatory limits. Such results offer proof of concept that the utilization of such lands for agriculture is possible.

4 Polluted lands for floriculture

The cultivation of edible plants on polluted lands would even if successful be under continual scrutiny because of the potential for accumulation of pollutants in edible tissues (Dziubanek et al. 2015). Another approach could be to restrict cultivation to non-food crops, such as those used for floriculture, horticulture, biomass, biofuels or production of commercially important chemicals (Lal et al. 2008; Jamil et al. 2009). In this context, cultivating ornamental plants on contaminated lands is a logical choice as it provides economic benefits, aesthetic value and possibly also ecological services during propagation to birds, honeybees, butterflies and other species (Lal et al. 2008; Ling-Zhi et al. 2011). There is likely to be increased demand of flowers and other ornamental plants in the future as the standard of living improves in many parts of the world (Wang and Zhou 2005). This creates a potential future scenario where floriculture crops will also compete with food crops for arable lands. Shifting floriculture production to contaminated lands could represent a viable strategy (Table 1). Species like marigold (*Tagetes* sp.) (Lal et al. 2008; Chatterjee and Singh 2012), scarlet sage (*Salvia splendens* L.), sweet hibiscus (*Abelmoschus manihot* L.) (Wang and Zhou 2005), chrysanthemum (*Chrysanthemum indicum* L.) (Lal et al. 2008; González-Chávez and Carrillo-González 2013), gladiolus (*Gladiolus grandiflorus* Andrews) (Lal et al. 2008), sunflower (*Helianthus annuus* L.) (Chatterjee and Singh 2012) and cock's comb (*Celocia cristata* L.) are already being tested in fields (Lal et al. 2008; Ling-Zhi et al. 2011; Wang and Zhou 2005). Native ornamental species growing near to the polluted sites can also be used for floriculture as they show plasticity and ability to grow in polluted soils (e.g., metal excluders) (de Abreu et al. 2012). For example, species of *Cistus* thrive in metal-contaminated soils. *Cistus populifolius* and *C. salviifolius* and their hybrid *Cistus* × *hybridus* showed tolerance to hazardous metals and are non-accumulators of As, Cu, Pb, Fe and Sb (de Abreu et al. 2012). Similarly, *Erica australis*, *E. andevalensis*, *Lavandula luisierra*, *Daphne gnidium*, *Rumex induratus*, *Ulex eriocladus*, *Juncus* and *Genista hirsutus* showed metal tolerance when grown on sites contaminated with multiple metals (Anawar et al. 2011). Continued research such as this is essential to maximize the profitability and ensure the safety of ornamentals produced on polluted lands.

5 Polluted lands for biomass and biofuel production

Fuel versus food production is another global debate as it involves competition for available land. Shifting biomass and biofuel production to polluted land could be a promising approach to overcome this competition (Cai et al. 2011; Edrisi and Abhilash 2016). Moreover, the production of biofuel crops from polluted lands may also

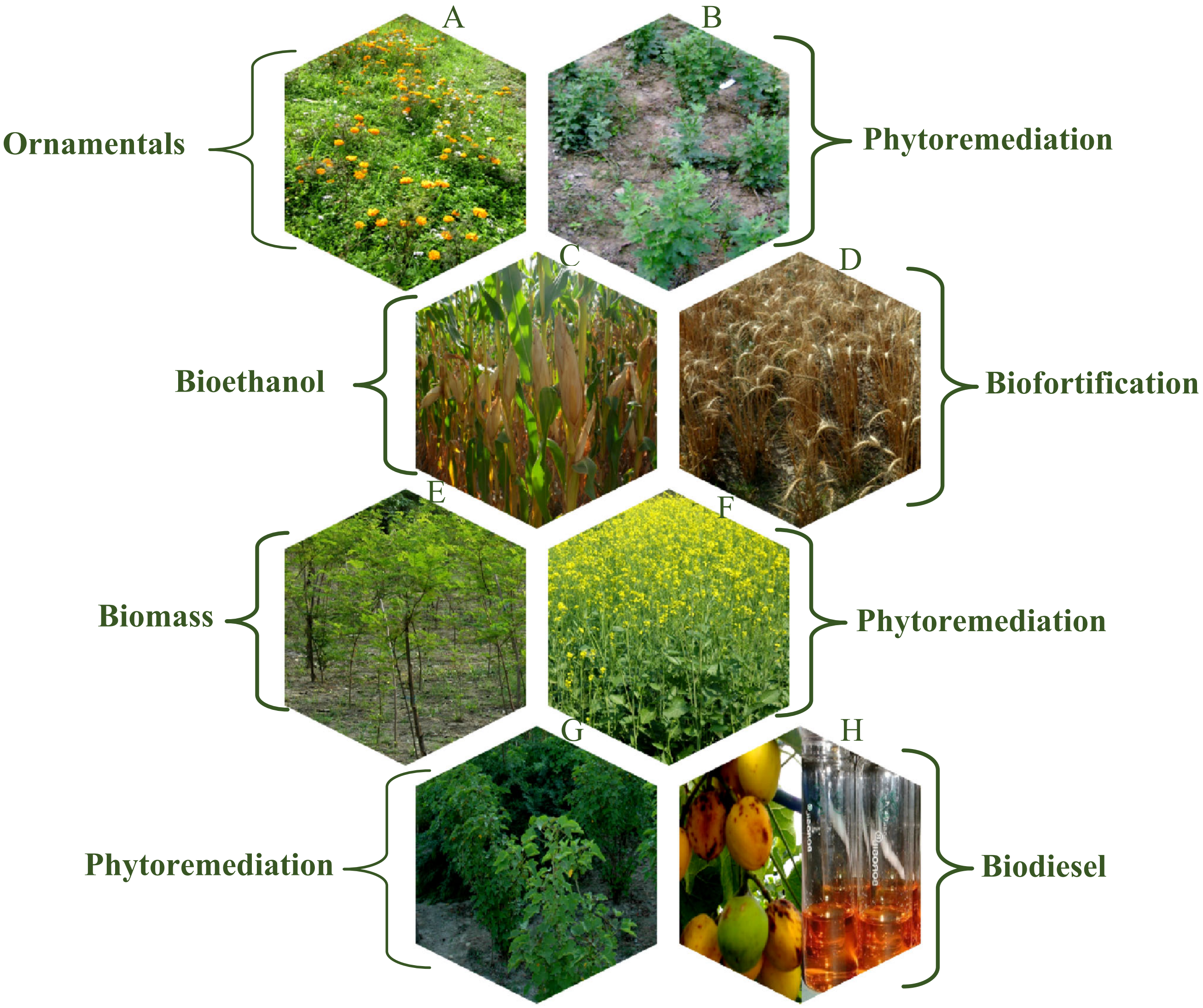


Fig. 1 Hexagons represent multipurpose species for bioremediation and economic returns from polluted soil. *A* Marigold (Lal et al. 2008) and *B* Chrysanthemum (González-Chávez and Carrillo-González 2013) are candidate species for floriculture. *C* Maize can be used for bioethanol production (Meers et al. 2010), *D* Wheat can be used for biofortification, *E* White leadtree can be cultivated for biomass production in organic and inorganic pollutants contaminated soil (Abhilash et al. 2013a, b), *F* Indian mustard is a well-known accumulator for toxic metals, *G* Jatropha growing in flyash dumps (photo credit: Sara Jamil) and *H* Biofuel extracted from Jatropha seeds (Edrisi et al. 2015)

reduce CO_2 emissions and pollution (Delucchi 2006). There are several candidate species that could be considered, such as physic nut (*Jatropha curcas* L.), white leadtree (*Leucena leucocephala* (Lam.) de Wit), castor bean (*Ricinus cummunis* L.), Indian beech (*Pongamia pinnata* L. Panigrahi), poplar (*Populus* sp.), switchgrass (*Panicum virgatum* L.) and *Miscanthus giganteus* that are known to have the potential to grow in polluted and degraded land (Cai et al. 2011; Olivares et al. 2013; Tang et al. 2010). Physic nut is usually well adapted to arid to semiarid climate and can grow in marginal lands, fly ash dumps and pesticide-contaminated soils (Edrisi et al. 2015; Abhilash et al. 2013a, b; Edrisi and Abhilash 2016). Similarly, leadtree and castor bean have the potential to grow and remediate soils contaminated with either organic or inorganic pollutants or a mixture of both the pollutants. These species showed a capacity to accumulate contaminants like Cd ($0.43\ \mathrm{mg\ kg^{-1}}$) and DDTs ($2.27\ \mathrm{mg\ kg^{-1}}$) (Huang et al. 2011). Poplar is another promising species that can grow in many multi-contaminant sites (e.g., TCE and heavy metals) (Weyens et al. 2013). The hybrid *M. giganteus* has potential to grow in Cd-, Zn- and Pb-contaminated (Pavel et al. 2014) lands and also has a significant potential for bioethanol

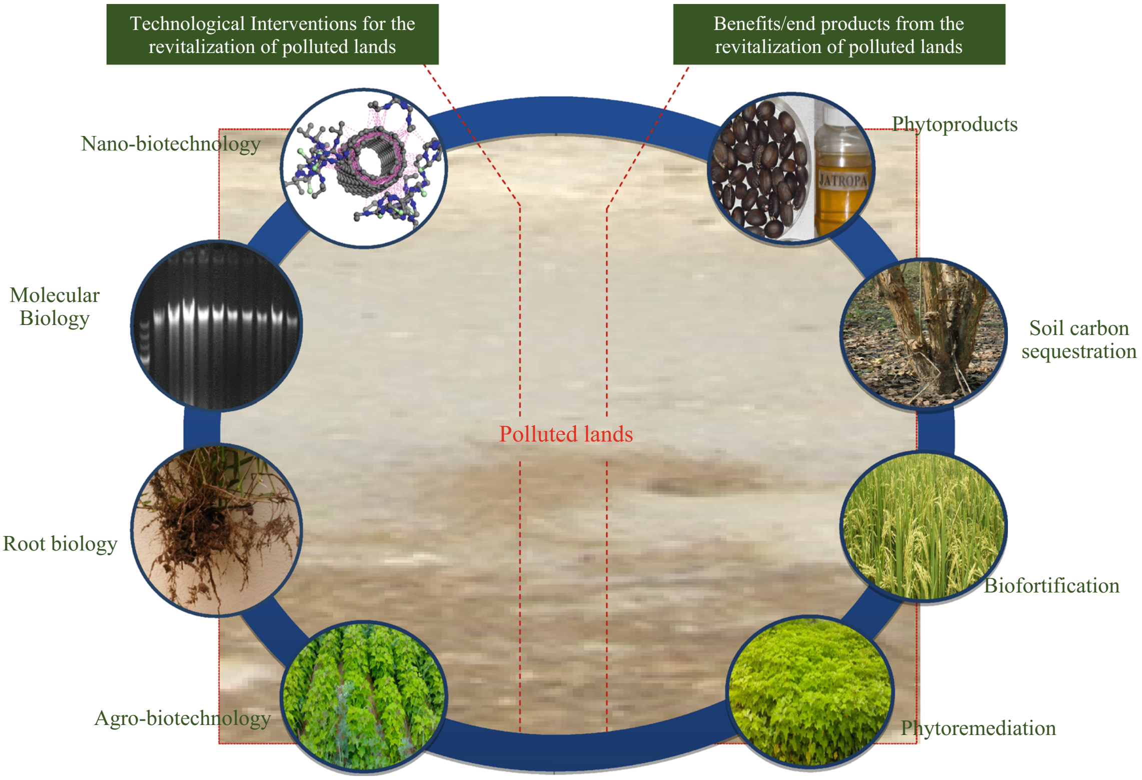


Fig. 2 Strategies for enhancing the sustainability of crop production from polluted lands. The application of agrobiotechnology, root biology, molecular biology and nano-biotechnology can be used for crop production from such lands (Germaine et al. 2009; Hur et al. 2011; Houben et al. 2013; El-Temsah 2013; Meister et al. 2014; Abhilash and Dubey 2015)

production (Chen et al. 2011). A recent field study revealed that among the naturally growing plants on heavy metal-contaminated sites, three biofuel plants, castor bean, prickly acacia (*Acacia nilotica* L.), and *Acacia modesta* (Wall.) were found to have the potential to accumulate Fe, Zn, Cr, Pb, Ni, As and Cd (Irshad et al. 2014). Several other potential biofuel crops like common reed (*Phragmites australis* L.), *Eucalyptus* spp., camelina (*Camelina sativa* L. Crantz), wild cane (*Arundo donax* L.), hemp (*Cannabis sativa* L.), Indian mustard (*B. juncea* L. Czern), linseed and corn have been reported to grow successfully on single or mixed-pollutants lands (e.g., Cd, Cr, Cu, Mn, Pb, Zn, PAH, Atrazine, Cs, Ni, Co and Se) (Madejón et al. 2011; Rayman et al. 2008; Meers et al. 2010; Bonanno et al. 2013; Ruttens et al. 2011; Doty et al. 2009; Kline and Coleman 2010; Fairley 2011; Técher et al. 2011; Vandenhove and Hees 2005; Zaidi et al. 2006; Willscher et al. 2013; Bauddh and Singh 2012; Van Slycken et al. 2013; Murakami et al. 2007). Utilizing contaminated lands for biomass and biofuel production could not only increase energy security but may increase job opportunities and improve stakeholder involvement.

6 Strategies for minimizing the uptake and accumulation of toxic pollutants in edible parts

Perhaps the most significant concern is that the cultivation of edible plants on contaminated lands will lead to the accumulation of pollutants in edible parts and in excess of the regulatory limits (Ye-Tao et al. 2012). Preventing potential health risks is one of the major challenges for the large-scale exploitation of polluted lands for crop production. Although most of the plants have the inherent capacity to detoxify the pollutants, the complete detoxification or elimination of the accumulated pollutant does not occur (Abhilash et al. 2009). Hence, plants can in some situations biomagnify the pollutant in the food chain (Köhler and Triebskorn 2013). Additionally, the presence of toxic of pollutants in the contaminated lands may hamper the establishment, growth and yield of the crop plants. These detrimental effects may be accentuated if the polluted soil lacks the necessary nutrients or beneficial microorganisms necessary for adequate growth and development (Abhilash et al. 2013a, b). These conditions create the need for site-specific agronomic practices and agrotechnological interventions to enhance the plant growth under adverse conditions while also restricting the transfer of toxic pollutants to the phytoproducts (Dubey et al. 2014; Tripathi et al. 2014a, b, 2015a, b). Such strategies must be targeted toward (1) selecting and breeding for low-accumulating cultivars (phytoexcluders) for polluted lands, (2) reducing the bioavailability of pollutants in the soil and (3) restricting the uptake and translocation of pollutants to edible parts (Ye-Tao et al. 2012). The ensuing sections briefly highlight various strategies that can be employed to achieve these endpoints (Fig. 2).

Previous studies reported that the accumulation of pollutants in plants depends to a significant degree upon the plant species, cultivar and species-specific traits. For example; Ye-Tao et al. (2012) extensively reviewed the differences in the uptake of heavy metals among different cultivars of rice, maize, wheat and soybean (*Glycine max* L). A comprehensive screening of suitable species for cultivars with reduced accumulation is an important step in the cropping of polluted lands. Once suitable species/cultivars are identified, site-specific and crop-specific agronomic practices can be optimized to enhance the plant–microbe interactions, increase nutrient and fertilizer efficiency, and reduce the toxicity and phytoavailability of the pollutants (Gilbert 2013; Abhilash et al. 2012). Chemical immobilization, for example, is a cost-effective way to reduce the heavy metal uptake in plants through the addition of soil amendments such as lime-, phosphate- and silicon-based materials, or adsorption agents (e.g., zeolites, iron oxides, manganese oxides and clay minerals) (Ye-Tao et al. 2012; Kashem et al. 2010). Similarly, organic amendments such as peat, biochar, manure, sludge, agricultural residues, compost or vermicompost are potentially favorable as they reduce the availability of the pollutant to plants and also provide nutrients to plants. These amendments may also support microbial consortia capable of degrading organic pollutants. For example, Houben et al. (2013) reported that the addition of 10 % biochar to heavy metal-contaminated soil enhanced the production of rape seed while reducing the heavy metal concentration of Cd, Zn and Pb by 71, 87 and 92 %, respectively (Houben et al. 2013). Similarly, amending polluted soil with activated carbon, charcoal or compost reduced the dissolved PAH concentrations as well their uptake and accumulation in radish (Marchal et al. 2014). Humic acid has been recommended as an amendment to facilitate biofortification (Vamerali et al. 2014), whereas chelating agents were reported to be helpful in reducing the toxicity of metals. Crop rotation, soil tillage, intercropping, capping, drip irrigation, inoculation of plant growth-promoting rhizobacteria (PGPR) and endophytes and application of microbial enzymes can also enhance the bioremediation of soil contaminants and improve plant growth with reduced accumulation of pollutants in edible parts (Karigar and Rao 2011; Rao et al. 2010; Tripathi et al. 2013; Segura and Ramos 2013; Vishnoi and Srivastava 2008; Álvareza et al. 2012; Wang et al. 2004). Such agronomic practices can enhance the plant–microbe interactions necessary for sustainable agriculture on polluted lands.

Rhizospheric engineering is another approach to modify the rhizospheric environment to improve the fertility of contaminated lands while also degrading pollutants in the root zone (Kumar 2013; Abhilash and Dubey 2015). Such manipulations can change the soil microbial community structure (Hur et al. 2011), AMF colonization (Gao et al. 2012) and endophytic microbial association (Germaine et al. 2009). Furthermore, novel microbial strains and new degradation pathways could be identified from polluted system using the metatranscriptomics and metaproteomics approaches (Machado et al. 2012; Junttila and Rudd 2012). Advances in genomics and the identification of quantitative trait loci (QTLs) for variety of agricultural traits offer great opportunity to identify traits that could be exploited to enhance the growth, yield and stress tolerance of crops grown in contaminated soil. Root genetics is another promising avenue to be explored for modification of root architecture, rhizoremediation of pollutants, increased water use efficiency and improved nutrient uptake, translocation and use efficiency (Meister et al. 2014; Villordon et al. 2014; Tian et al. 2014; Schmidt 2014).

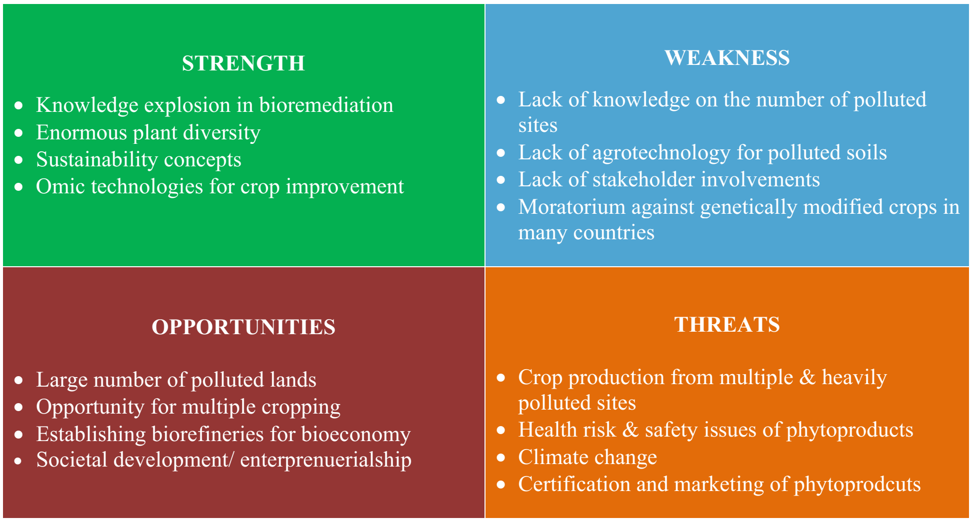
Exploring nanotechnology for enhancing the degradation of pollutants (nanoremediation) in contaminated site is another promising approach to minimize the entry of toxic pollutants into the plant parts (Karn et al. 2009). Nanoparticles (NPs) like nZVI, ZnO, TiO_2, carbon nanotubes, fullerenes and bimetallic nanometals can be used for soil remediation (Karn et al. 2009). NPs can immobilize soil heavy metals such as Cr(VI), Pb(II), As(III) and Cd in contaminated soils and reduce the concentration of heavy metals in leachates to values lower than the soil elution standard regulatory threshold (Mallampati et al. 2013). NPs can also mediate redox reactions that convert heavy metals such as Cr(VI) to their less toxic trivalent form Cr(III) in tannery waste contaminated soil. The TCLP-leachable Pb fraction decreased from 66 to 10 % in a Pb-contaminated fire range soil following addition of NPs (Singh et al. 2012; Liu and Zhao 2013). NPs are also being used for the degradation of organic pollutants such as carbamates, chlorinated organic solvents, DDT and PCBs (Zhang 2003; El-Temsah 2013). The contaminated land remediated by nanoparticles could further be used for agricultural production. As with any emerging technology, nanotechnology too has its potential risks and benefits that need to be examined closely if it is to be developed and used for contaminated land remediation.

7 Concluding remarks and future perspectives

The continual increase in the human population coupled with scarcity of new arable lands creates the need to explore polluted lands for food production and other useful endpoints. However, there are many outstanding questions (Table 2) to be answered before the large-scale exploitation of such polluted lands for agricultural production can be implemented. It would be difficult at present to measure the sustainability of crop production from polluted land as currently there are no valuation techniques or benchmarks for evaluating the performance of a phytoremediation-based bioeconomy. As proposed in Fig. 3, a detailed SWOT analysis is the first and foremost step toward the exploitation of such polluted lands for crop production. The recent knowledge explosion in bioremediation coupled with the concepts of sustainability and plant biodiversity is the greatest strength of such innovative practices. Moreover, the large expanses of contaminated land offer opportunities for multiple cropping for food production as well as biorefineries for bioeconomy. However, the lack of agrotechnology for cropping in polluted soils and moratoriums against the use of GM crops in many countries are major setbacks for such efforts. Crop production on multiple and heavily polluted sites represents significant challenges, particularly given the health and safety risks associated with the phytoproducts. Specific agrotechnological interventions must be optimized for cropping on polluted lands, and suitable cultivars should be selected through genetic and molecular breeding. Public perception regarding this use of contaminated land must be changed and greater awareness of the need created. There is also a need for greater stakeholder involvement. Potential conflicts of interest (if any) between different stakeholders must be properly addressed and proper monitoring and eco-toxicological risk assessments should be done at each and every stages of cropping. Importantly, the certification and marketing of phytoproducts will be a great challenge and proper regulatory mechanisms should be established to ensure the safety of such products in the marketplace.

Table 2 Outstanding questions regarding the sustainability of crop production from polluted lands

Sl no.	Outstanding questions
1	How can inventories of the polluted lands in low income and developing countries be produced to identify their potential for bioeconomy?
2	What are the key sustainability challenges for the crop production from multiple and heavily contaminated sites?
3	How can the general public be convinced of the safety of phytoproducts?
4	What are the issues associated with the certification of phytoproducts from polluted lands?
5	Can systems biology and root biology offer new solutions for the sustainable utilization of polluted lands?
6	How effective will the production of phytoproducts from polluted lands be under changing climate?



STRENGTH

- Knowledge explosion in bioremediation
- Enormous plant diversity
- Sustainability concepts
- Omic technologies for crop improvement

WEAKNESS

- Lack of knowledge on the number of polluted sites
- Lack of agrotechnology for polluted soils
- Lack of stakeholder involvements
- Moratorium against genetically modified crops in many countries

OPPORTUNITIES

- Large number of polluted lands
- Opportunity for multiple cropping
- Establishing biorefineries for bioeconomy
- Societal development/ enterprenuerialship

THREATS

- Crop production from multiple & heavily polluted sites
- Health risk & safety issues of phytoproducts
- Climate change
- Certification and marketing of phytoprodcuts

Fig. 3 SWOT analysis for exploiting polluted lands for crop production

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Compliance with ethical standards

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