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P. C. Abhilash

Vishal Tripathi

Sheikh Edrisi

Rama Dubey

Mansi Bakshi

See next page for additional authors

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Authors

P. C. Abhilash, Vishal Tripathi, Sheikh Edrisi, Rama Dubey, Mansi Bakshi, Pradeep Dubey, H. B. Singh, and Stephen Ebbs

Trends in Plant Science
Review

Sustainability of crop production from polluted lands

P.C Abhilash[1]*♣, Vishal Tripathi[1]♣, Rama Kant Dubey[1]♣, Sheikh Adil Edrisi[1]♣,
Mansi Bakshi[1], M.N.V.Prasad[2], H.B. Singh[3]

[1]Institute of Environment & Sustainable Development, Banaras Hindu University, Varanasi 221005, India
[2]Department of Plant Sciences, University of Hyderabad, Hyderabad 500046, Telangana, India
[3]Institute of Agricultural Sciences, Banaras Hindu University, Varanasi 221005, India

*Corresponding Author: Email: pca.iesd@bhu.ac.in
♣Contributed equally

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 to 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 to the phytoproducts, certification and marketing of such products, in order to achieve a the large scale exploitation of polluted lands.

Key words: Polluted lands; Crop production; Sustainability; Bioeconomy; Phytoproducts

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

Our planet earth will be inhabited by about 9.5 billion people by the mid of this century [1]. Such an explosive rise in population will demand an additional 70% increase in food, feed and fiber [2] production. Therefore, the greatest challenges in this century is to increase the food production for a rapidly growing population as outlined in the recently framed sustainable development goals (SDGs) of UN [3]. However, land is a limited resource and the growing population itself needs additional land for habitation and developmental activities. Furthermore, any modifications in the existing land use will affect the resilience of ecological and socio-economic systems [4]. Therefore, the dilemma is to increase the crop production without encroaching additional land area for agriculture [5]. Moreover, the challenges will become severe under changing climatic conditions as it is projected to affect the weather pattern, growth, yield and diseases prevalence in crops. The changing climate will also reduce the nutritional quality of crops [6]. Hence, it is the need of the hour to frame suitable strategies for increasing the global food production without any additional pressure on planetary boundaries [7-8].

Though there are many strategic and applied studies were undertaken to testify the immense potential of ‘omic technologies’ for customizing crops for enhanced productivity, nutritional quality and stress tolerance; there is a growing public outcry against the use of GM crops for meeting the global food demand [9]. Moreover, GM crops are less preferred by public due to their perceived safety and ethical considerations and lack of scientific understanding [10]. While agricultural intensification through increased inputs and mechanization has been suggested as an immediate strategy for maximizing the global food demand, the excessive use of agrochemicals during the last few decades had already resulted in the severe pollution of biosphere [11-12]. Hence, ~25% of the global land resources are highly degraded and ~44% are moderately degraded and the level of contamination is steadily increasing all over the world. Therefore, the successful exploitation of **polluted lands** will provide an additional avenue for **agricultural extensification** (see Glossary). However, there are many challenging issues including the possible entry of pollutants into to the **phytoproducts** (see box 1) must be addressed before the crop production from such lands. In this perspective, the present review examine the sustainability of crop production from polluted lands and provide suitable strategies for converting polluted lands to an agricultural landscape for fostering a **bioeconomy** [13] for sustainable development.

Crop production from polluted lands: An environmental point of view

Land is a critical resource as it supports various life forms by providing nutrients and minerals, maintaining biogeochemical cycle, agricultural production facilitating and providing other numerous services for human wellbeing and good quality of life. It also acts as a primary sink of pollutants [14]. Conversely, the growing population exerts tremendous pressure on land for food, feed, fiber and biofuel production. It is estimated that we will be required an additional area of about 2.7- 4.9 Mha /year to meet the food demand of growing populations [8]. Therefore, the agricultural extensification to newer landscapes at the coast of forests, wetlands and grass lands is not a sustainable option as it accelerates the biodiversity loss and other environmental issues [15]. By adopting suitable scientific and technological interventions, the polluted lands can be utilized for agricultural production [8]. Though such lands are generally perceived as a potential threat to the human beings, the scarcity of arable lands will inevitably compel us to exploit it as an untapped resource for environmental **sustainability** [11, 16].

Therefore, exploiting polluted lands for agriculture will not only fulfill the target of the food demand of growing populations but also to restoring the ecosystem services of such degraded systems. Furthermore, polluted lands can also to meet out the energy demands by cultivating suitable biomass and biofuel crops [16]. Such polluted lands can also be exploited for combating the nutrient deficiency by adopting suitable **biofortification** strategies for the agricultural produce [17]. Nevertheless, there are many ecotoxicological, economic and social considerations are associated with the crop production from polluted lands and all concerns must be thoroughly addressed before using such lands for any agricultural venture [18]. The impending sections provides (i) a state-of-art on the crop productions from polluted lands (ii) strategies for minimizing the potential risk to human beings and converting crop production from polluted lands as a sustainable enterprise.

Polluted lands for edible crop production and biofortification

A selected list of crop plants being tested at field and controlled conditions are provided in **Table1**. The uptake and accumulation of pollutants in crops varied with species or cultivars, type of pollutants and level of contamination [19-20]. For instance, a field trial in a moderately Cd contaminated (0.69 to 0.96 mg kg^{-1}) land in China based on a rotation system of rape seed to rice restricted the phytoaccumulation of Cd in rice. The rape seed cultivar Zhucang Huzai accumulated high Cd concentration (>0.2 mg kg^{-1}) where as the Cd concentration in cultivar Chuanyou II-93 was well below the limit. Similarly, Cd concentrations of the brown rice were below the permissible limits [21]. The concentrations of As, Cu, Co, Pb and Zn in cassava (*Manihot esculenta* Crantz) growing on the contaminated soils of the Zambian copper belt was reported by Kribek et al [22]. Interestingly, the level of Cu in leaves and tubers of cassava grown in strongly contaminated areas do not exceed the daily maximum tolerance limit (0.5 mg kg^{-1} / human body weight). However, the highest tolerable weekly ingestion of Pb and As exceeded in the vicinity of smelters.

Warren et al [23] conducted a detailed field trial to assess the uptake of As by beet root, calabrese, cauliflower, lettuce, potato, radish, and spinach growing on As contaminated soil (748 mg kg^{-1}) near to an As smelter in Cornwall, UK and enhanced the remediation process by the precipitation of Fe oxides in the contaminated soils by adding ferrous sulfate and lime. In all field trials except for spinach, ferrous sulfate addition significantly reduced the As translocation to edible parts. Moreover, the application of 02% Fe oxides in upper soil column (0-10 cm) reduced the As uptake by 22%; whereas the 0.5% Fe oxides reduced the As availability by 32% [23] . Madejon et al [24] employed traditional agricultural practices in a heavily contaminated soils in Southern Spain to limit the accumulation of As, Cu, Pb and Zn in onion, lettuce, chard, potato and lemon. The metal content was low in crops with annual liming and animal manure applications [24]. In all cases except for Zn and Pb, the accumulation of metals was within the statutory limits. The heavy metal accumulations in vegetables growing on a contaminated fluvial deposit of Gilgit, Pakistan [19] shown that the level of Cd (0.24- 2.1 mg kg^{-1}), Pb (15-44 mg kg-1) and Zn (40-247 mg kg^{-1}) was above the permissible limit.

Biofortification of edibles is another avenue that could be achieved through cropping on soil polluted with essential micronutrients like Fe, Zn, Cu Mg, and Se [25-26]. Se is an important dietary micronutrient required for plants, animals and human beings [24]. SeMet is the major Se species in several grains like barley, wheat, rye, etc. contributing to about 60–80% of the total Se content [27]. X-ray absorption near edge spectroscopic analysis of a rice sample obtained from a Se contaminated region of Enshi district in South-Central China reveals that rice can also be predominantly consisted of SeMeSeCys beside SeMet [28]. SeMeSeCys is believed to confer anti-carcinogenic properties. Moreover, both SeMeSeCys and SeMet provide supplementary health benefits over inorganic Se [29-30]. Unfortunately, the Se levels in the rice were reported to have only 33% to 50% [31]. Since soils contaminated with Se are reported worldwide, these soils can be used for cropping Se accumulating crops for bifortification. Se can also lower the uptake of Pb in rice thereby lowering the accumulation of Pb in grains [21]. Hence cropping on Se contaminated soils reduces the uptake of other pollutants as well. The Linseed growing on contaminated soils with essential metals like Fe, Cu and Zn enhanced the plant height and number of capsule per plant [32]. Therefore, cultivating linseed in metal contaminated soil would enhance the nutritionally important microelements in seeds. Vamerali et al [26] studied the biofortification and remediation potential of radish and maize cultivated in a pyrite waste dump at Torviscosa (Udine), Italy. Although the accumulation of various heavy metals in maize grains (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 be lower, the concentrations of Cd (2.34) and Pb (4.20) in Radish was higher than the permissible limit of EU. There are studies reported the accumulation of toxic metals in edible parts within the safe limit. For example, the Cd, Pb, Zn accumulation in maize grain [33]; As accumulation in beet root and lettuce [23]; Ni concentration in carrot and onion [34] etc were within the limit. The above cases indicate that crop productions from contaminated lands are being widely pursued across the world (**Figure 1 and 2**) and there is ample scope for the utilization of such lands for agriculture as in many cases the accumulation level was within the safe limit.

Polluted lands for floriculture

The cultivation of edibles on polluted lands is always under scrutiny as crops can transfer pollutants to the edible parts [35]. Hence it is advisable to use non-edibles but they can also offer other value additions like flowers, biomass, biofuel and other industrially important chemicals [36-37]. In this context, cultivating ornamentals in contaminated lands is a wise choice as it provide economic benefits, aesthetic appearance and improved ecological services as the flowers can also attract birds, honeybees, butterflies and other sensitive species [36,38]. Moreover, the demand of flowers and other ornamental plants will be higher in future as the living standard of the people will further improve in many parts of the world [39]. So it is anticipated that, in future, floriculture crops will also compete with food crops for cultivable lands. Hence, it would be better to support floriculture in contaminated lands (**Table 1**). Species like Marigold (*Tagetes* sp.) [36,40], Scarlet sage (*Salvia splendens*), Sweet hibiscus (*Abelmoschus manihot*) [39], Chrysanthemum (*Chrysanthemum indicum* L.) [36, 41], Gladiolus (*Gladiolus grandiflorus* Andrews) [36], Sunflower (*Helianthus annuus*) [40], and Cock's comb (*Celocia cristata*) are already being tested in fields [36, 38-39, 42-43]. 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 (for e.g. metal excluders). For example, *Cistus* sp. is a similar plant that thrives well in metal contaminated soils. *C. populifolius* and *C. salviifolius* and their hybrid *Cistus* × *hybridus* showed tolerance to hazardous metals as these plants are non-accumulators of As, Cu, Pb, Fe and Sb [44]. Similarly, *Erica australis*, *E. andevalensis*, *Lavandula luisierra*, *Daphne gnidium*, *Rumex induratus*, *Ulex eriocladus*, *Juncus*, and *Genista hirsutus* showed metal tolerance in multi metal contaminated sites [45]. However, suitable research frameworks are essential to maximize the profitability and ensure the safety of ornamentals from polluted lands.

Polluted lands for biomass and biofuel production

Fuel versus food production is another global debate as land availability is a limiting factor for both cases. Hence, biomass and biofuel production from polluted land is appreciated as a promising approach to overcome the potential conflict between food and fuel production [46]. Moreover, the production of biofuel crops from polluted lands will also reduce the CO_2 emissions and pollution [47]. There are several candidate species like *Jatropha curcas, Leucena leucocephala, Ricinus cummunis, Pongamia pinnata, Populus* sp., *Miscanthus giganteous, Panicum virgatum* etc that are known to have the potential to grow in polluted and degraded land [46, 48-49]. *Jatropha curcas* is usually well adapted to arid to semi-arid climate and can grow in marginal lands, fly ash dumps and pesticide contaminated soils [50-51]. Similarly *L. leucocephala* and *R. communis* have the potential to grow and remediate the land contaminated with either organic or inorganic or a mixture of both the pollutants as it has greater accumulation potential for contaminants like Cd (0.43 mg kg^{-1}) and DDTs (2.27 mg kg^{-1}) [52]. Poplar is another promising species that can grow in many co-contaminated sites (TCE and heavy metals) [53]. Hybrid of *M. sinensis x giganteus* has potential to grow in Cd, Zn and Pb contaminated [54] lands and also have huge potential for bioethanol production [55]. A recent field study revealed that among the naturally growing plants on heavy metal contaminated sites, three biofuel plants *R. communis, Acacia nilotica,* and *A. modesta* were found to have high accumulation potential Fe, Zn, Cr, Pb, Ni, As and Cd [56]. Apart from that, many other potential biofuel crops like *Phragmites australis, Populus* spp., *Eucalyptus* spp., *Camelina sativa, Arundo donax, M. giganteous, Cannabis sativa, B. juncea, Linum usitatissimum, Zea mays etc* have been reported to grown in specific or mixed pollutants lands (Cd, Cr, Cu, Mn, Pb, Zn, PAH, Atrazine, Cs, Ni, Co and Se) [24, 30, 33, 57-68]. Hence, apart from achieving the energy security, the bioenergy productions from polluted lands will also ensure the job opportunities and stakeholders' involvement.

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

There is a major apprehension that the cultivation of edible plants on contaminated lands can leads to the accumulation of pollutants in edible parts with their concentrations exceeding the statutory limits [69]. The health risk posed by such accumulated pollutants in phytoprodcuts 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 of the accumulated pollutant does not happen in many times [70]. Hence the pollutants can magnify at the subsequent level of the food chain [71]. Apart from that, the presence of toxic of pollutants in the contaminated lands will hamper the growth and establishment of crop plants itself. Moreover, the lack of desired nutrients and microorganisms in polluted soil will also badly affect the growth and establishment [11] of crops in such lands. Therefore, it is essential to develop contaminated site-specific agronomic practices and agro-technological interventions to enhance the plant growth under adverse conditions and restrict the transfer of toxic pollutants to the phytoproducts. Importantly, such strategies must be targeted towards the (i) selection and breeding of low-accumulating cultivars (phytoexcluders) for polluted lands (ii) reducing the bioavailability of pollutants in the soil and (iii) restricting the uptake and translocation of pollutants to edible parts [69]. The ensuing sections briefly highlight various strategies that can be employed for crops production from contaminated lands (**Key Figure 3**).

Previous studies reported that the accumulation of pollutants in plants is mainly depends upon plant i.e. cultivar and species specific traits. For example; Ye-Tao et al [69] extensively reviewed the differences in the uptake of heavy metals among different cultivars of rice, maize, wheat and soybeans. Therefore, the screening of suitable species or cultivars with lower accumulation trait is an important step in the cropping of polluted lands. Once suitable species/cultivars were selected, site specific and crop specific agronomic practices can be optimized to enhance the plant-microbe interactions in the contaminated and also for reducing the toxicity and phytoavailability of the pollutants [10, 72-73]. Chemical immobilization is a cost-effective way to reduce the heavy metal uptake in plants through the addition of chemical amendments in soil like lime, phosphate and silicon based materials, adsorption agents such as zeolites, iron oxides, manganese oxides, clay minerals etc [69, 74]. Similarly, the organic amendments such as peat, biochar, animal excrement, sludge, agro-residues, compost, vermin-compost etc are preferably favorable as they reduce the availability of the pollutant to plants and also provide nutrients to plants and facilitating the microbial degradation of the pollutants. For example, Houben et al. [75] reported that the amendment of 10% biochar to heavy metal contaminated soil enhanced the production of *Brassica napus* L while reducing the heavy metal concentration by 71, 87 and 92%, respectively, for Cd, Zn and Pb [75]. Similarly, polluted soil amended with activated carbon, charcoal or compost reduced the dissolved PAH concentrations in soil as well their uptake and accumulation in *Raphanus sativus* L. [76]. Humic acid is recommended for biofortification [26] where as chelating agents were reported to be helpful in reducing the toxicity of metals. Crop rotation, soil tillage, intercropping, capping, drip irrigation, inoculation of PGPR and **endophytes**, application of **microbial enzymes** etc can also enhances the **bioremediation** and plant growth in contaminated soil with reduced accumulation of pollutants in edible parts [78-84]. Such agronomic practices can enhance the plant-microbe interactions for the sustainable agriculture from polluted lands.

Rhizospheric engineering is another approach to modify the rhizospheric environment for improving the fertility of contaminated lands while degrading the pollutants in root zone itself [85]. Importantly, such manipulations can change the soil microbial community structure [86], AMF colonization [87], and in endophytic microbial association [88]. Furthermore, novel microbial strains and new degradation pathways can be identified from polluted system using the metatranscriptomics and metaproteomics approaches [89-90]. Advancement in genomics helps in exploring the quantitative trait loci (QTLs) for variety of agricultural crops offering great opportunity for enhancing the growth, yield and stress tolerance in contaminated soil. Root genetics is another promising aspect to be explored for **root architecture modification** and **rhizoremediation** of pollutants [91]. With altering the root biology we can modify the root architecture [92-93], nutrient uptake, translocation and use efficiency, water use efficiency etc [91,94].

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. [95]. Nanoparticles (NPs) like, nZVI, ZnO, TiO_2, carbon nanotubes, fullerenes, bimetallic nanometal can be used for soil remediation [95]. 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 [96]. NPs can also convert heavy metals such as Cr (VI) to their less toxic trivalent form Cr (III) in tanner waste contaminated soil and decrease the TCLP-leachable Pb fraction from 66% to 10% in a Pb-contaminated fire range soil [97-98]. NPs are also being used for degradation of organic pollutants such as carbamates, chlorinated organic solvents, DDT, PCBs etc [99-100]. These contaminated land remediated by nanoparticles could be further 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.

Concluding remarks and future perspectives

The population explosion coupled with scarcity of arable lands will compel human being to explore polluted lands for food production and other useful commodities. However, there are many outstanding questions (**see Box 2**) to be answered before the large scale exploitation of such polluted lands for agricultural production. Moreover, it is difficult to measure the sustainability of crop production from polluted land as currently we do not have any valuation techniques or benchmarks for evaluating the performance of a phytoremediation based bioeconomy. As proposed in **Figure 4**, a detailed SWOT analysis is the first and foremost step towards the exploitation of such polluted lands for crop production. The recent knowledge explosion in bioremediation coupled with the notion of sustainability and enormous plant diversity are the greatest strength of such innovative practices. Moreover, the vast number of contaminated lands offers opportunities for multiple cropping for food production as well as biorefineries for bioeconomy. However, lack of agrotechnology for cropping in polluted soils and moratorium against the use of GM crops in most of the countries is a major setback to such efforts. Moreover, the crop production from multiple and heavily polluted sites is a serious challenge and pose health risk and safety issues of phytoprodcuts. Hence suitable agrotechnological interventions must be optimized for cropping in polluted lands and suitable cultivars should be selected through genetic and molecular breeding. The perception of peoples towards the contaminated lands must be changed through proper awareness creation and stakeholder involvements. Potential conflict of interest (if any) between different stakeholders must be properly addressed and proper monitoring and eco-toxicological risk assessment should be done at each and every stages of cropping. Importantly, the certification and marketing of phytoprodcuts will be a great challenge and proper regulatory mechanism should be enforced to ensure the safety of such products available in markets.

Conflict of interest

Authors do not have any conflict of interest

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Glossary

Amendment: for the purpose of the review, ‘amendment’ means the modification of the physical, chemical or biological properties of the soil by the addition of any chemical or biological materials.

Bioeconomy: the economy entirely based on biological resources and biobased activities.

Biodiesel: a renewable form of energy obtained from the phytobiomass consisting of long chain alkyl esters.

Biorefinery: the concept of farming and production of biodiesel and other biomaterials from polluted lands

Bioremediation: the use of living organisms or their products i.e. enzymes for the remediation of polluted system.

Biofortification: the enrichment of the nutritional quality especially the micronutrients in food crops.

Endophytes: the microorganisms inhabiting inside the plant tissues which help in plant growth promotion and phytoremediation efficiency of the plant.

Microbial enzymes: are the enzymes produced by microorganisms which help in the reduction, degradation and removal of pollutants.

Nanoremediation: is a kind of remediation that uses material of nanometric size for the remediation of polluted environment.

Polluted lands: is a kind of degraded land due to the contamination of chemical pollutants such as heavy metals, pesticides, poly aromatic hydrocarbons etc.

Phytoextraction: is the removal/extraction of pollutants from the environment using plants.

Phytohormones: are the regulatory hormones produced by plants.

Phytoproducts: the different plant produces such as biomass, seed, fruit, biofuel, biocomposite etc obtained during the phytoremediation of polluted lands.

Rhizoremediation: the stabilization/degradation of pollutants in the root system due to the enhanced microbial activity and root secretions.

Figure Legends

Figure 1. Multipurpose species for remediation and economic returns from polluted soil. **(A)** Chrysanthemum species (**B)** Wheat good candidate for biofortification **(C)** Maize for bioethanol **(D)** Tagetes (E) *Leucena leucocephala* for biomass production (F) *Brassica juncea* a well known hyperaccumulator for toxic metals [33, 36, 43].

Figure 2. Bioethanol production from polluted lands. **(A)** *Moringa oleifera* growing in the polluted peri-urban areas of Hyderabad, India (**B)** Fruit (drum stick) **(C)** Seed **(D)** Biodiesel from Moringa (E) *Jatropha curcas* growing on the fly ash dumps (Sonebhadra, Uttar Pradesh) (F) Jatropha seeds (G) Biodiesel from Jatropha [104]

Key Figure 3. Strategies for enhancing the sustainability of crop production from polluted lands. The application of agro-biotechnology, root biology, molecular biology and nano-biotechnology can be used for the crop production from such lands [113-116].

Figure 4: SWOT analysis for exploiting polluted lands for crop production.