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3 Sustainability of crop production from polluted lands

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13
14 Sustainable food production for a rapidly growing global population is a major challenge of
15 this century. In order to meet the demand for food production, an additional land area of 2.7 to
16 4.9 Mha year⁻¹ will be required for agriculture. However, one third of arable lands are already
17 contaminated, therefore the use of polluted lands will have to feature highly in modern
18 agriculture. The use of such lands comes however with additional challenges and suitable
19 agrotechnological interventions are essential for ensuring the safety and sustainability of
20 relevant production system. There are also other issues to consider such as, cost benefit
21 analysis, the possible entry of pollutants into the phytoproducts, certification and marketing
22 of such products, in order to achieve a the large scale exploitation of polluted lands.

23
24 **Key words:** Polluted lands; Crop production; Sustainability; Bioeconomy; Phytoproducts

25 26 **Increasing crop production for a growing population: the need of the hour**

27 Our planet earth will be inhabited by about 9.5 billion people by the mid of this century
28 [1]. Such an explosive rise in population will demand an additional 70% increase in food, feed
29 and fiber [2] production. Therefore, the greatest challenges in this century is to increase the
30 food production for a rapidly growing population as outlined in the recently framed sustainable
31 development goals (SDGs) of UN [3]. However, land is a limited resource and the growing
32 population itself needs additional land for habitation and developmental activities.
33 Furthermore, any modifications in the existing land use will affect the resilience of ecological
34 and socio-economic systems [4]. Therefore, the dilemma is to increase the crop production
35 without encroaching additional land area for agriculture [5]. Moreover, the challenges will
36 become severe under changing climatic conditions as it is projected to affect the weather
37 pattern, growth, yield and diseases prevalence in crops. The changing climate will also
38 reduce the nutritional quality of crops [6]. Hence, it is the need of the hour to frame suitable
39 strategies for increasing the global food production without any additional pressure on
40 planetary boundaries [7-8].

41
42 Though there are many strategic and applied studies were undertaken to testify the
43 immense potential of 'omic technologies' for customizing crops for enhanced productivity,
44 nutritional quality and stress tolerance; there is a growing public outcry against the use of GM
45 crops for meeting the global food demand [9]. Moreover, GM crops are less preferred by
46 public due to their perceived safety and ethical considerations and lack of scientific
47 understanding [10]. While agricultural intensification through increased inputs and
48 mechanization has been suggested as an immediate strategy for maximizing the global food

49 demand, the excessive use of agrochemicals during the last few decades had already
50 resulted in the severe pollution of biosphere [11-12]. Hence, ~25% of the global land
51 resources are highly degraded and ~44% are moderately degraded and the level of
52 contamination is steadily increasing all over the world. Therefore, the successful exploitation
53 of **polluted lands** will provide an additional avenue for **agricultural extensification** (see
54 **Glossary**). However, there are many challenging issues including the possible entry of
55 pollutants into to the **phytoproducts** (see box 1) must be addressed before the crop
56 production from such lands. In this perspective, the present review examine the sustainability
57 of crop production from polluted lands and provide suitable strategies for converting polluted
58 lands to an agricultural landscape for fostering a **bioeconomy** [13] for sustainable
59 development.

61 **Crop production from polluted lands: An environmental point of view**

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

75
76 Therefore, exploiting polluted lands for agriculture will not only fulfill the target of the
77 food demand of growing populations but also to restoring the ecosystem services of such
78 degraded systems. Furthermore, polluted lands can also to meet out the energy demands by
79 cultivating suitable biomass and biofuel crops [16]. Such polluted lands can also be exploited
80 for combating the nutrient deficiency by adopting suitable **biofortification** strategies for the
81 agricultural produce [17]. Nevertheless, there are many ecotoxicological, economic and social
82 considerations are associated with the crop production from polluted lands and all concerns
83 must be thoroughly addressed before using such lands for any agricultural venture [18]. The
84 impending sections provides (i) a state-of-art on the crop productions from polluted lands (ii)
85 strategies for minimizing the potential risk to human beings and converting crop production
86 from polluted lands as a sustainable enterprise.

87 **Polluted lands for edible crop production and biofortification**

88 A selected list of crop plants being tested at field and controlled conditions are
89 provided in **Table1**. The uptake and accumulation of pollutants in crops varied with species or
90 cultivars, type of pollutants and level of contamination [19-20]. For instance, a field trial in a
91 moderately Cd contaminated (0.69 to 0.96 mg kg⁻¹) land in China based on a rotation system
92 of rape seed to rice restricted the phytoaccumulation of Cd in rice. The rape seed cultivar
93 Zhucang Huzai accumulated high Cd concentration (>0.2 mg kg⁻¹) where as the Cd
94 concentration in cultivar Chuanyou II-93 was well below the limit. Similarly, Cd concentrations
95 of the brown rice were below the permissible limits [21]. The concentrations of As, Cu, Co, Pb
96

97 and Zn in cassava (*Manihot esculenta* Crantz) growing on the contaminated soils of the
98 Zambian copper belt was reported by Kribek et al [22]. Interestingly, the level of Cu in leaves
99 and tubers of cassava grown in strongly contaminated areas do not exceed the daily
100 maximum tolerance limit (0.5 mg kg⁻¹ / human body weight). However, the highest tolerable
101 weekly ingestion of Pb and As exceeded in the vicinity of smelters.

102
103 Warren et al [23] conducted a detailed field trial to assess the uptake of As by beet
104 root, calabrese, cauliflower, lettuce, potato, radish, and spinach growing on As contaminated
105 soil (748 mg kg⁻¹) near to an As smelter in Cornwall, UK and enhanced the remediation
106 process by the precipitation of Fe oxides in the contaminated soils by adding ferrous sulfate
107 and lime. In all field trials except for spinach, ferrous sulfate addition significantly reduced the
108 As translocation to edible parts. Moreover, the application of 0.2% Fe oxides in upper soil
109 column (0-10 cm) reduced the As uptake by 22%; whereas the 0.5% Fe oxides reduced the
110 As availability by 32% [23]. Madejon et al [24] employed traditional agricultural practices in a
111 heavily contaminated soils in Southern Spain to limit the accumulation of As, Cu, Pb and Zn in
112 onion, lettuce, chard, potato and lemon. The metal content was low in crops with annual
113 liming and animal manure applications [24]. In all cases except for Zn and Pb, the
114 accumulation of metals was within the statutory limits. The heavy metal accumulations in
115 vegetables growing on a contaminated fluvial deposit of Gilgit, Pakistan [19] shown that the
116 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
117 permissible limit.

118
119 Biofortification of edibles is another avenue that could be achieved through cropping on
120 soil polluted with essential micronutrients like Fe, Zn, Cu Mg, and Se [25-26]. Se is an
121 important dietary micronutrient required for plants, animals and human beings [24]. SeMet is
122 the major Se species in several grains like barley, wheat, rye, etc. contributing to about 60–
123 80% of the total Se content [27]. X-ray absorption near edge spectroscopic analysis of a rice
124 sample obtained from a Se contaminated region of Enshi district in South-Central China
125 reveals that rice can also be predominantly consisted of SeMeSeCys beside SeMet [28].
126 SeMeSeCys is believed to confer anti-carcinogenic properties. Moreover, both SeMeSeCys
127 and SeMet provide supplementary health benefits over inorganic Se [29-30]. Unfortunately,
128 the Se levels in the rice were reported to have only 33% to 50% [31]. Since soils
129 contaminated with Se are reported worldwide, these soils can be used for cropping Se
130 accumulating crops for biofortification. Se can also lower the uptake of Pb in rice thereby
131 lowering the accumulation of Pb in grains [21]. Hence cropping on Se contaminated soils
132 reduces the uptake of other pollutants as well. The Linseed growing on contaminated soils
133 with essential metals like Fe, Cu and Zn enhanced the plant height and number of capsule
134 per plant [32]. Therefore, cultivating linseed in metal contaminated soil would enhance the
135 nutritionally important microelements in seeds. Vamerali et al [26] studied the biofortification
136 and remediation potential of radish and maize cultivated in a pyrite waste dump at Torviscosa
137 (Udine), Italy. Although the accumulation of various heavy metals in maize grains (mg kg⁻¹)
138 such as Cd (<0.001); Co (<0.002); Cr (0.12); Cu (3.28) Mn (6.17); Ni (0.41); Pb (<0.001) and
139 Zn (40.2) was found be lower, the concentrations of Cd (2.34) and Pb (4.20) in Radish was
140 higher than the permissible limit of EU. There are studies reported the accumulation of toxic
141 metals in edible parts within the safe limit. For example, the Cd, Pb, Zn accumulation in
142 maize grain [33]; As accumulation in beet root and lettuce [23]; Ni concentration in carrot and
143 onion [34] etc were within the limit. The above cases indicate that crop productions from
144 contaminated lands are being widely pursued across the world (Figure 1 and 2) and there is

145 ample scope for the utilization of such lands for agriculture as in many cases the
146 accumulation level was within the safe limit.

147
148
149

150 **Polluted lands for floriculture**

151 The cultivation of edibles on polluted lands is always under scrutiny as crops can
152 transfer pollutants to the edible parts [35]. Hence it is advisable to use non-edibles but they
153 can also offer other value additions like flowers, biomass, biofuel and other industrially
154 important chemicals [36-37]. In this context, cultivating ornamentals in contaminated lands is
155 a wise choice as it provide economic benefits, aesthetic appearance and improved ecological
156 services as the flowers can also attract birds, honeybees, butterflies and other sensitive
157 species [36,38]. Moreover, the demand of flowers and other ornamental plants will be higher
158 in future as the living standard of the people will further improve in many parts of the world
159 [39]. So it is anticipated that, in future, floriculture crops will also compete with food crops for
160 cultivable lands. Hence, it would be better to support floriculture in contaminated lands (Table
161 1). Species like Marigold (*Tagetes* sp.) [36,40], Scarlet sage (*Salvia splendens*), Sweet
162 hibiscus (*Abelmoschus manihot*) [39], Chrysanthemum (*Chrysanthemum indicum* L.) [36, 41],
163 Gladiolus (*Gladiolus grandiflorus* Andrews) [36], Sunflower (*Helianthus annuus*) [40], and
164 Cock's comb (*Celocia cristata*) are already being tested in fields [36, 38-39, 42-43]. Native
165 ornamental species growing near to the polluted sites can also be used for floriculture as they
166 show plasticity and ability to grow in polluted soils (for e.g. metal excluders). For example,
167 *Cistus* sp. is a similar plant that thrives well in metal contaminated soils. *C. populifolius* and *C.*
168 *salviifolius* and their hybrid *Cistus x hybridus* showed tolerance to hazardous metals as these
169 plants are non-accumulators of As, Cu, Pb, Fe and Sb [44]. Similarly, *Erica australis*, *E.*
170 *andevalensis*, *Lavandula luisierra*, *Daphne gnidium*, *Rumex induratus*, *Ulex eriocladus*,
171 *Juncus*, and *Genista hirsutus* showed metal tolerance in multi metal contaminated sites [45].
172 However, suitable research frameworks are essential to maximize the profitability and ensure
173 the safety of ornamentals from polluted lands.

174

175 **Polluted lands for biomass and biofuel production**

176 Fuel versus food production is another global debate as land availability is a limiting
177 factor for both cases. Hence, biomass and biofuel production from polluted land is
178 appreciated as a promising approach to overcome the potential conflict between food and fuel
179 production [46]. Moreover, the production of biofuel crops from polluted lands will also reduce
180 the CO₂ emissions and pollution [47]. There are several candidate species like *Jatropha*
181 *curcas*, *Leucena leucocephala*, *Ricinus cummunis*, *Pongamia pinnata*, *Populus* sp.,
182 *Miscanthus giganteous*, *Panicum virgatum* etc that are known to have the potential to grow in
183 polluted and degraded land [46, 48-49]. *Jatropha curcas* is usually well adapted to arid to
184 semi-arid climate and can grow in marginal lands, fly ash dumps and pesticide contaminated
185 soils [50-51]. Similarly *L. leucocephala* and *R. communis* have the potential to grow and
186 remediate the land contaminated with either organic or inorganic or a mixture of both the
187 pollutants as it has greater accumulation potential for contaminants like Cd (0.43 mg kg⁻¹) and
188 DDTs (2.27 mg kg⁻¹) [52]. Poplar is another promising species that can grow in many co-
189 contaminated sites (TCE and heavy metals) [53]. Hybrid of *M. sinensis x giganteus* has
190 potential to grow in Cd, Zn and Pb contaminated [54] lands and also have huge potential for
191 bioethanol production [55]. A recent field study revealed that among the naturally growing
192 plants on heavy metal contaminated sites, three biofuel plants *R. communis*, *Acacia nilotica*,

193 and *A. modesta* were found to have high accumulation potential Fe, Zn, Cr, Pb, Ni, As and Cd
194 [56]. Apart from that, many other potential biofuel crops like *Phragmites australis*, *Populus*
195 spp., *Eucalyptus* spp., *Camelina sativa*, *Arundo donax*, *M. giganteous*, *Cannabis sativa*, *B.*
196 *juncea*, *Linum usitatissimum*, *Zea mays* etc have been reported to grown in specific or mixed
197 pollutants lands (Cd, Cr, Cu, Mn, Pb, Zn, PAH, Atrazine, Cs, Ni, Co and Se) [24, 30, 33, 57-
198 68]. Hence, apart from achieving the energy security, the bioenergy productions from polluted
199 lands will also ensure the job opportunities and stakeholders' involvement.

200

201 **Strategies for minimizing the uptake and accumulation of toxic pollutants in edible** 202 **parts**

203 There is a major apprehension that the cultivation of edible plants on contaminated
204 lands can leads to the accumulation of pollutants in edible parts with their concentrations
205 exceeding the statutory limits [69]. The health risk posed by such accumulated pollutants in
206 phytoproducts is one of the major challenges for the large scale exploitation of polluted lands
207 for crop production. Although most of the plants have the inherent capacity to detoxify the
208 pollutants, the complete detoxification of the accumulated pollutant does not happen in many
209 times [70]. Hence the pollutants can magnify at the subsequent level of the food chain [71].
210 Apart from that, the presence of toxic of pollutants in the contaminated lands will hamper the
211 growth and establishment of crop plants itself. Moreover, the lack of desired nutrients and
212 microorganisms in polluted soil will also badly affect the growth and establishment [11] of
213 crops in such lands. Therefore, it is essential to develop contaminated site-specific agronomic
214 practices and agro-technological interventions to enhance the plant growth under adverse
215 conditions and restrict the transfer of toxic pollutants to the phytoproducts. Importantly, such
216 strategies must be targeted towards the (i) selection and breeding of low-accumulating
217 cultivars (phytoexcluders) for polluted lands (ii) reducing the bioavailability of pollutants in the
218 soil and (iii) restricting the uptake and translocation of pollutants to edible parts [69]. The
219 ensuing sections briefly highlight various strategies that can be employed for crops production
220 from contaminated lands (Key Figure 3).

221

222 Previous studies reported that the accumulation of pollutants in plants is mainly
223 depends upon plant i.e. cultivar and species specific traits. For example; Ye-Tao et al [69]
224 extensively reviewed the differences in the uptake of heavy metals among different cultivars
225 of rice, maize, wheat and soybeans. Therefore, the screening of suitable species or cultivars
226 with lower accumulation trait is an important step in the cropping of polluted lands. Once
227 suitable species/cultivars were selected, site specific and crop specific agronomic practices
228 can be optimized to enhance the plant-microbe interactions in the contaminated and also for
229 reducing the toxicity and phytoavailability of the pollutants [10, 72-73]. Chemical
230 immobilization is a cost-effective way to reduce the heavy metal uptake in plants through the
231 addition of chemical amendments in soil like lime, phosphate and silicon based materials,
232 adsorption agents such as zeolites, iron oxides, manganese oxides, clay minerals etc [69,
233 74]. Similarly, the organic amendments such as peat, biochar, animal excrement, sludge,
234 agro-residues, compost, vermin-compost etc are preferably favorable as they reduce the
235 availability of the pollutant to plants and also provide nutrients to plants and facilitating the
236 microbial degradation of the pollutants. For example, Houben et al. [75] reported that the
237 amendment of 10% biochar to heavy metal contaminated soil enhanced the production of
238 *Brassica napus* L while reducing the heavy metal concentration by 71, 87 and 92%,
239 respectively, for Cd, Zn and Pb [75]. Similarly, polluted soil amended with activated carbon,
240 charcoal or compost reduced the dissolved PAH concentrations in soil as well their uptake

241 and accumulation in *Raphanus sativus* L. [76]. Humic acid is recommended for biofortification
242 [26] where as chelating agents were reported to be helpful in reducing the toxicity of metals.
243 Crop rotation, soil tillage, intercropping, capping, drip irrigation, inoculation of PGPR and
244 **endophytes**, application of **microbial enzymes** etc can also enhances the **bioremediation**
245 and plant growth in contaminated soil with reduced accumulation of pollutants in edible parts
246 [78-84]. Such agronomic practices can enhance the plant-microbe interactions for the
247 sustainable agriculture from polluted lands.
248

249 Rhizospheric engineering is another approach to modify the rhizospheric environment
250 for improving the fertility of contaminated lands while degrading the pollutants in root zone
251 itself [85]. Importantly, such manipulations can change the soil microbial community structure
252 [86], AMF colonization [87], and in endophytic microbial association [88]. Furthermore, novel
253 microbial strains and new degradation pathways can be identified from polluted system using
254 the metatranscriptomics and metaproteomics approaches [89-90]. Advancement in genomics
255 helps in exploring the quantitative trait loci (QTLs) for variety of agricultural crops offering
256 great opportunity for enhancing the growth, yield and stress tolerance in contaminated soil.
257 Root genetics is another promising aspect to be explored for **root architecture modification**
258 and **rhizoremediation** of pollutants [91]. With altering the root biology we can modify the root
259 architecture [92-93], nutrient uptake, translocation and use efficiency, water use efficiency etc
260 [91,94].
261

262 Exploring nanotechnology for enhancing the degradation of pollutants
263 (**nanoremediation**) in contaminated site is another promising approach to minimize the entry
264 of toxic pollutants into the plant parts. [95]. Nanoparticles (NPs) like, nZVI, ZnO, TiO₂, carbon
265 nanotubes, fullerenes, bimetallic nanometal can be used for soil remediation [95]. NPs can
266 immobilize soil heavy metals such as Cr (VI), Pb (II), As (III), and Cd in contaminated soils
267 and reduce the concentration of heavy metals in leachates to values lower than the soil
268 elution standard regulatory threshold [96]. NPs can also convert heavy metals such as Cr (VI)
269 to their less toxic trivalent form Cr (III) in tanner waste contaminated soil and decrease the
270 TCLP-leachable Pb fraction from 66% to 10% in a Pb-contaminated fire range soil [97-98].
271 NPs are also being used for degradation of organic pollutants such as carbamates,
272 chlorinated organic solvents, DDT, PCBs etc [99-100]. These contaminated land remediated
273 by nanoparticles could be further used for agricultural production. As with any emerging
274 technology, nanotechnology too has its potential risks and benefits that need to be examined
275 closely if it is to be developed and used for contaminated land remediation.
276

277 **Concluding remarks and future perspectives**

278 The population explosion coupled with scarcity of arable lands will compel human
279 being to explore polluted lands for food production and other useful commodities. However,
280 there are many outstanding questions (see Box 2) to be answered before the large scale
281 exploitation of such polluted lands for agricultural production. Moreover, it is difficult to
282 measure the sustainability of crop production from polluted land as currently we do not have
283 any valuation techniques or benchmarks for evaluating the performance of a
284 phytoremediation based bioeconomy. As proposed in Figure 4, a detailed SWOT analysis is
285 the first and foremost step towards the exploitation of such polluted lands for crop production.
286 The recent knowledge explosion in bioremediation coupled with the notion of sustainability
287 and enormous plant diversity are the greatest strength of such innovative practices.
288 Moreover, the vast number of contaminated lands offers opportunities for multiple cropping for

289 food production as well as biorefineries for bioeconomy. However, lack of agrotechnology for
290 cropping in polluted soils and moratorium against the use of GM crops in most of the
291 countries is a major setback to such efforts. Moreover, the crop production from multiple and
292 heavily polluted sites is a serious challenge and pose health risk and safety issues of
293 phytoproducts. Hence suitable agrotechnological interventions must be optimized for cropping
294 in polluted lands and suitable cultivars should be selected through genetic and molecular
295 breeding. The perception of peoples towards the contaminated lands must be changed
296 through proper awareness creation and stakeholder involvements. Potential conflict of interest
297 (if any) between different stakeholders must be properly addressed and proper monitoring
298 and eco-toxicological risk assessment should be done at each and every stages of cropping.
299 Importantly, the certification and marketing of phytoproducts will be a great challenge and
300 proper regulatory mechanism should be enforced to ensure the safety of such products
301 available in markets.

302

303 **Conflict of interest**

304 Authors do not have any conflict of interest

305

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Glossary

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

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

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

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

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

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

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

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

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

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

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

611 **Phytohormones:** are the regulatory hormones produced by plants.

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

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

616

617 **Figure Legends**

618 **Figure 1.** Multipurpose species for remediation and economic returns from polluted soil. **(A)**

619 Chrysanthemum species **(B)** Wheat good candidate for biofortification **(C)** Maize for

620 bioethanol **(D)** Tagetes (E) *Leucena leucocephala* for biomass production (F) *Brassica juncea*

621 a well known hyperaccumulator for toxic metals [33, 36, 43].

622

623 **Figure 2.** Bioethanol production from polluted lands. **(A)** *Moringa oleifera* growing in the

624 polluted peri-urban areas of Hyderabad, India **(B)** Fruit (drum stick) **(C)** Seed **(D)** Biodiesel

625 from Moringa (E) *Jatropha curcas* growing on the fly ash dumps (Sonebhadra, Uttar Pradesh)

626 (F) *Jatropha* seeds (G) Biodiesel from *Jatropha* [104]

627

628

629 **Key Figure 3.** Strategies for enhancing the sustainability of crop production from polluted

630 lands. The application of agro-biotechnology, root biology, molecular biology and nano-

631 biotechnology can be used for the crop production from such lands [113-116].

632

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

634