Brassicaceae Plants Response and Tolerance to Metal/Metalloid Toxicity

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Abstract Brassicaceae is an important Family having numerous numbers of genera and species within it. Some of these species are important food crops specifically oilseed and vegetables, some are weeds also. They have significant role in accumulation of heavy metals like cadmium, arsenic, lead, caesium, uranium, zinc, etc. in their tissues and have the potential genes within them which attribute tolerance/resistance against the ill effect of these metals. These plants naturally clean and ameliorate the soil contaminated with metal/metalloids. Under Brassicaceae family, members like *Brassica juncea, Brassica oleracea, Brassica napus, Brassica carinata* and many more are known for their phytoremediation property. Like, the seedlings of *B. oleracea, B. juncea* and *Raphanus sativus* are found to uptake arsenic by their root and shoot both. Also, some of the species are known for huge accumulation of heavy metals in tissues which may be a source of potential new genes widening the future research work on phytoremediation. Therefore keeping the worlds' increasing population in mind many of them can be well adapted for growing commercially in heavy metal contaminated soil to contribute to the food basket of the world. The goal of this article is to review the use of species under Brassicaceae family in phytoremediation.

Keywords Heavy metals · Brassica crops · Oilseeds · Phytoextraction · Phytoremediation

Abbreviations

Cd	Cadmium
Cr	Chromium

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Mo	Molybdenum
Zn	Zinc
Mn	Manganese
Pb	Lead
As	Arsenic
Ni	Nickel
DW	Dry weight
EDTA	Ethylene Diamine Tetra Acetic Acid
ROS	Reactive Oxygen Species

1 Introduction

Brassicaceae is an important plant family contains genus Brassica. This genus is also important from agriculture point of view because it contains 39 species. It ranks among world's first ten most important plant families with high economic value of the world (Warwick et al. 2000). There are 375 genera and 3200 species under the umbrella Brassicaceae. It is also called as mustard family. Also there are a number of cultivated and hybrids of cultivated species. The species with their high dietary fibre has possessed a valuable place in the list of food crops with their large variation of economic parts starting from oil bearing seeds, stems, buds, flowers, roots and leaves which are used as vegetables, leafy greens, salad, spices, oils, etc. (Hasanuzzaman 2008). Within genus Brassica, *Brassica juncea, Brassica carinata, Brassica rapa, Brassica campestris* and *Brassica napus*—these six species are altogether called as Rapeseed-mustard group. Rapeseed-Mustard being the main oilseed crop is planted on more than 80% area covered under oilseeds. Their seed bear oil and contributes 35% of total oilseeds crops in India (Table 1) (Nmoop 2018). According to FAOSTAT (2013) Brassica oilseeds occupies more than 34 million ha land annually over the world. In 1935, UN has given the relationship between these six species in a form of a triangle, designated as U's triangle (Fig. 1).

Also some very common vegetables like cabbage, cauliflower, broccoli, Brussels sprout, kohlrabi, collards and kale come under *Brassica oleraceae* species. They are known for high nutritional value. The other vegetable Brassicaceae includes *B. napus, B. rapa*, *Raphanus sativus, Lepidium sativum* and *Nasturtium officinale.* The condiment crops include *B. juncea*, *Sinapis alba*, *Brassica nigra*, *Armoracia rusticana* and *Eutrena japonica.* Still there are numbers of crops which are being used as potherbs and salads. Among a number of weedy species, *Sinapis arvensis, Raphanus raphanistrum*, *B. rapa* and *Hirschfeldia incana* are of greatest interest with regard to cross-pollination with *B. napus.* Among wild relatives of Brassica, species like *Begonia. adpressa, Brassica fruticulosa, Brassica pinescens, Brassica oxyrrhina, Brassica barrelieri and Brassica tournefortii* comes under the group *Brassica coenospecies*. They are known for their good agronomic characteristics and used

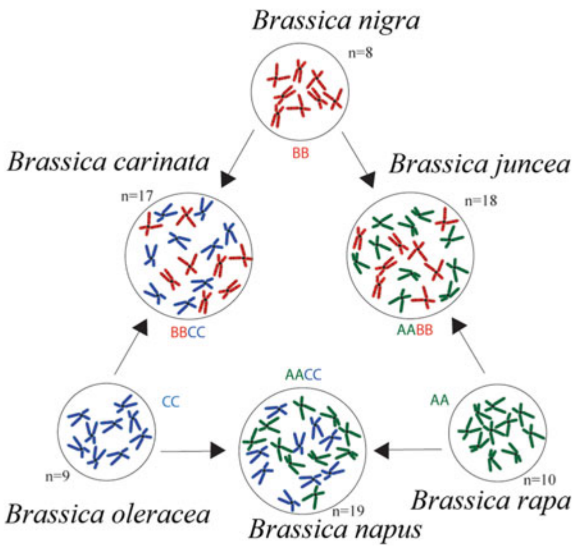

Fig. 1 U's triangle (*Source* UN 1935)

widely in hybridization programme (Warwick 1993). The genus *Brassica* is classified as follows:

Order Brassicales (= Cruciales)

Family Brassicaceae (= Cruciferae)

Tribe Brassiceae

Subtribe Brassicinae

Genus *Brassica* L.

Under Brassicaceae, there are 25 tribes with a supplementary 5 currently under study (Al-Shehbaz et al. 2006). Brassiceae contains the genus *Brassica* and wild relatives has 48 genera and near about 240 species (Table 2) (Warwick and Hall 2009). As the population is increasing, it is providing pace to the industrialization also; and the whole, leads to the exposure of the toxic matters as waste materials directly or indirectly to the environment. All the major parts of the environment—air, soil and water are contaminated highly by these toxics to such extent that it has become a life threat to humankind (Zhuang et al. 2007), as well as for animal and plant kingdom (Singh et al. 2011; Hasanuzzaman et al. 2012; Hasanuzzaman and Fujita 2012). These include metal, metalloids, radio nucleotides and different kinds of environmental contaminants. Human activities related to industries and agricultural practices expose the environment to various heavy metals and metalloids like Molybdenum, Cadmium, Arsenic, Nickel, Cobalt, etc. (Pilon-Smits 2005). There is very less or narrow chance to find out a remedy (Cunningham et al. 1997; Prasad and Freitas 2003). Though there are policies and routine precautions and a big list of Do's and DON'Ts, which is not enough to control the heavy metal pollution of the earth (Zayad and Tery 2003). There is a huge pressure of providing enough food to supply a square meal to this burgeoning population of the world. Horizontal expansion of cultivable land is not possible until the degraded, polluted and waste fallows are being converted to cultivated one. But these contaminated and marginal lands are always a threat to food production with a huge chance of food contamination when used for cultivation (He et al. 2005). But nature has always an answer to every situation. Thangahu et al. (2011) reported about development of different techniques to judge and observe the status and movement of metals inside the soil, water and wastewater. Again some plants/adopted a technique to extract, sequester and detoxify the toxic elements. The plant is known as accumulator plant. The technique is termed as Phytoremediation (Fig. 2) where the Greek originated prefix *Phyto* means plant and latin word remedium means to correct (Erakhrumen and Agbontalor 2007; Tangahu et al. 2011). From the observation of (USEPA 2000; Sarma 2011 and Tangahu et al. 2011), it can be stated that phytoremediation is comparatively cheap and ecofriendly method to get rid of the toxic materials from soil, water or air. Some specific plants are known to successfully engross contaminants include metals and metalloids responsible for environmental contamination. Phytoextraction being the significant process, used to eliminate heavy metals from soil utilizing its ability to take up the essential nutrients which are contaminants too under specific conditions (Fe, Mn, Zn, Cu, Mg, Mo, and Ni). Besides, other metals with unidentified function (Cd, Cr, Pb, Co, Ag, Se, Hg) can also be stored (Cho-Ruk et al. 2006). Among angiosperms, Brassicaceae is the most important family having the huge number

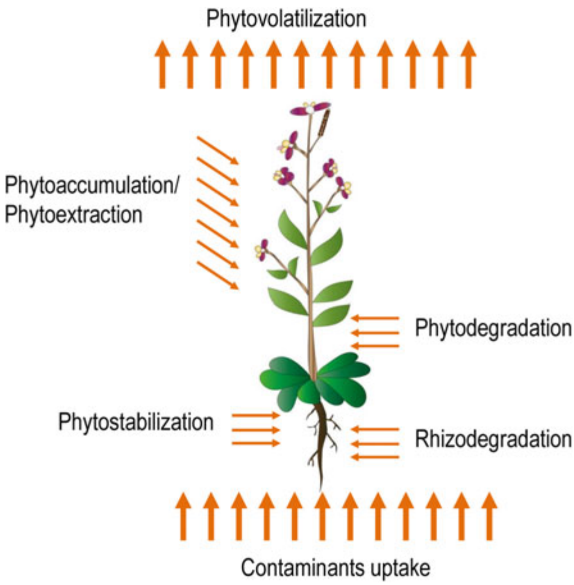

Fig. 2 Phytoremediation-the mechanism for heavy metal uptake by plants

of (25%) metal accumulating species (90) (Prasad and Freitas 2003; Palmer et al. 2001a, b; Krämer 2010; Sarma 2011). Some member of the family Brassicaceae can accumulate metals even the toxic ones in relatively high amount (Kumar et al. 1995 and Anjumet al. 2012). They are potential phytoextraction plants (Van Ginneken et al. 2007; Gall and Rajkaruna 2013) who show visible symptoms of metal accumulation and being the food crops they contaminate the food chain (Gall et al. 2015). Brassicas accumulate heavy metals in their stem due to the inherent tolerance to metals present in excess. Tangahu et al. (2011) observed that some of the member of Brassica genus (*B. campestris* L.*, B. carinata* A. Br.*, B. juncea* (L.) *Czern*) can accumulate lead in their tissue more than 50 mg g^{-1} dry weight of plant whereas *B. nigra* Koch. can gather more than 100 mg g^{-1} dry weight. From the same study we came to know that in case of mercury, *B. juncea* accumulated more than 1 mg g^{-1} dry weight compared to other species (<0.2 mg/g dry weight). Therefore they may be used as tool for phytoextraction (Neison and Rajkaruna 2012). Indian mustard or *B. juncea*, an important oil contributor in India has been reported to have a reduced oil percentage in seed due to accumulation of Cadmium (Ahmad et al. 2015; Mourato et al.2015). Not only Cadmium, according to Alkorta et al. (2004) and Szczyglowska et al. (2011), *B. juncea* has a superior capacity of different toxic metal accumulation. *Brassica napus* also known as rapeseed is the chief source of eatable oil in the world can accumulate Zn in its plant biomass (Grispenet al. 2006; Carrier et al. 2003). *Brassica campestris* also known as turnip rape, also an oilseed can also accumulate metals in its below ground parts (Gleba et al. 1999). It is considered for the phytoremediation of Chromium which can be accumulated in huge quantity by this species (Dheri et al. 2007). Kabata-Pendias (2001), from a study confirmed that *B. oleracea* accumulated lead (Pb) in good quantity. Kumar et al. (1995) observed that roots are more efficient in Pb accumulation than above ground parts. Gisbert found that not only Pb, it also accumulate Zn and Cu in its shoot. Addae (2010) observed in a study that *B. oleracea* species can extract significant amount of Cd and Pb. All these research work has been conducted with a focus in the matter to find out a plant which will be pretty good to be used for phytoremediation with the characters like, more accumulation efficiency in shoot, tolerance capacity in soils with high amount of metals, fast growing and easy to grow and harvest (Table 3) (Marchiol et al. 2004). Some of the best studies citing the role of Brassicaceae in tolerance to metals and metalloids are presented hereunder for better understanding.

2 Amelioration of Cadmium (Cd) Toxicity by *Coronopus didymus*

Coronopus didymus, a native of South America is an annual herb of family Brassicaceae and widely distributed across the world (Yannitsaros 1986). In Northern India, it is being grown along the road sides and gardens specifically during October to February. Sidhu et al. (2017) worked with *C. didymus* to assess the development and survival of *C. didymus* under varied Cd treatments and also on the tolerance and extraction efficiency of C. *didymus* under various levels of Cd concentrations. They reported that under 400 mg kg^{-1} Cd, there was an increase in Cd content in roots and shoots (867.2 and 864.5 mg kg^{-1} DW), reflecting the potential of this herb *C. didymus* in ameliorating the toxicity effect of Cd in soils. The possible explanation for this tolerance is the compartmentalization of metals in vacuoles that restricted the excess Cd transport in the plants. Besides, Phytochelatins has a significant role in accumulating Cd within roots (Zeng et al. 2009). Toxicity of Cd induces stress stimulates the generation and build-up of Reactive Oxygen Species (Devi et al. 2007). Enzymes like super oxide dismutase, catalase and peroxidase play a crucial role in quenching Reactive Oxygen Species (ROS) produced as because of heavy metal stress (Zhang et al. 2013). Due to the antioxidative responses, *C. didymus* could be one of the possible options to be used in Cd contaminated soils with no risk to human or animals as it is unpalatable and cannot enter the food chain.

3 Response of *Hirschfeldia incana* to Lead (Pb)

Lead (Pb) is one of the toxic elements having ill effect on the quality of environment as well as human health (Lee et al. 2005). Although it is not essential for plants, but still imposes a toxicity threat to plants and animals. Auguy et al. (2013) identified *Hirschfeldia incana*, a member of the Brassicaceae family, with a high potential to accumulate lead in their biomass. *Hirschfeldia incana* was formerly known as *Brassica geniculata* is a species of flowering plant in the mustard family with common names as shortpod mustard, buchan weed, hoary mustard and Mediterranean mustard. In their study, chosen area was heavily affected by lead mining contamination with a concentration range of 26–9479 mg kg^{-1} (Smouni et al. 2010). The Brassicaceae *H. incana* was found to be important for its ability to accumulate toxic heavy metals in leaves. *H. incana* was able to accumulate 106 mg Pb g^{-1} DW in roots at their vegetative growth and 77 mg Pb g^{-1} DW in roots at the floral stage after 60 days of lead exposure. In one of the study, Kaur (2018) identified the ability of Indian mustard with and without chelants like EDTA and salicylic acid. Pb concentrations increased in root and shoot organs of the plant with EDTA treatment, but it decreased with salicylic acid treatment. The results also revealed that *B. juncea var. arawali* accumulated high amount of Pb in roots with low translocation in the parts of shoots; nevertheless it could be used for phytoremediation of Pb (Tables 1 and 2).

4 Arsenic Tolerance by Brassicaceae Seedlings

Arsenic is one of the potential toxic elements with a high risk of entering food chains and one report by Bhattacharya et al. (2010) emphasize that 93% of the total arsenic are being consumed by humans. This consumption is always accompanied

Table 1 Year-wise production of major oilseeds in India (in Million tonnes)

Year	Groundnut	Rapeseed-mustard	Soybean	Sunflower
1950–51	3.48	0.76	–	–
1960–61	4.81	1.35	–	–
1970–71	6.11	1.98	0.01	0.08
1980–81	5.01	2.30	0.44	0.07
1990–91	7.51	5.23	2.60	0.87
2000–01	6.41	4.19	5.28	0.65
2010–11	8.26	8.18	12.74	0.65
2011–12	6.96	6.60	12.21	0.52
2012–13	4.70	8.03	14.67	0.54
2013–14	9.71	7.88	11.86	0.43
2014–15	7.40	6.28	10.37	0.43
2015–16	6.73	6.80	8.57	0.30
2016–17	7.46	7.92	13.16	0.25
2017–18	9.25	8.43	10.98	0.22
2018–19	6.52	8.78	13.74	0.20

Source Modified from Directorate of Economics and Statistics
Third Advance Estimates of Production of Commercial Crops for 2018–19

with a health hazard to human population as it is considered one of the most unsafe ingredients to humans (Khan et al. 2009). Numerous species of Brassicaceae are designated as arsenic tolerant to metals (Srivastava et al. 2009). Freitas-Silva et al. (2016) showed that even Brassicaceae seedlings at initial growing conditions can accumulate arsenic in their biomass (Table 4). Roots accumulated high arsenic when compared to shoots suggesting little movement of these metalloids to the shoots.

5 Hyperaccumulation of Selenium by Brassicaceae Crops

Seleniferous soils are those with high levels of selenium and there are some Brassicaceae species that can accumulate high levels of Se within their biomass (Brown and Shrift 1981). Plants can normally accumulate around 0.05–1 mg kg^{-1} Se dry weight, but there are hyperaccumulators too which can engross higher concentrations and occasionally hundreds of times more than the usual range of Se accumulated by normal plants. Hladun et al. (2011) studied the accumulation of Se in the plant parts of *Stanleya pinnata* and *B. Juncea. Stanleya pinnata was* found to be the efficient accumulator of selenium which has a potential to accumulate 22% (Nectar) and 85% (pollen) excess over *B. juncea. Stanleya pinnata* is a species under mustard family and also known as desert prince's plume and is a native to North America. The mechanism behind the accumulation of Se in *S. pinnata* is the mobilization of

Table 2 Cultivated *Brassica* species and related genera

Species name	Common name
Brassica rapa L.	
subsp. *Campestris* (L.) A.R. Clapham	Summer turnip rape, canola
subsp. *oleifera* (DC.) Metzg	Winter turnip rape
subsp. *campestris* (L.) A.R. Clapham	Bird or wild turnip rape
subsp. *trilocularis* (Roxb.) Hanelt	Yellow and brown Sarson
subsp. *dichotoma* (Roxb.) Hanelt	Toria
subsp. *chinensis* (L.) Hanelt	Pak-choi or bokchoy, Chinese mustard, chinese broccoli, GaiLan
subsp. *pekinensis* (Lour.) Hanelt	Pe-tsai, Chinese cabbage
subsp. *nipposinica* (L.H. Bailey) Hanelt	Curled mustard
subsp. *rapa*	Turnip
B.tournefortii Gouan	Wild turnip
B.nigra (L.) W.D.J. Koch	Black mustard
B. oleracea L.	
var. *viridis* L.	Kale, collard
var. *botrytis* L.	Cauliflower and broccoli
var. *capitata* L.	Cabbage
var. *Gongylodes*	Kohlrabi
var. *gemmifera* (DC.) Zenker	Brussels sprout
var. *italic* Plenck	Broccoli
var. *Oleracea*	Wild cabbage
subsp. *alboglabra* L.H. Bailey	Chinese kale, Kailan
B. juncea (L.) Czern.	Brown and oriental mustard, rai
B. napus L.	
var. *napus*	Summer oilseed rape, canola
var. *napus*	Winter oilseed rape, winter Canola
var. *pabularia* (DC.) Rchb.	Rape-kale
var. *napobrassica* (L.) Rchb.	Rutabaga, swede
B. carinata A. Braun.	Abyssinian mustard
Hirschfeldia incana (L.) Lagr.-Foss.	Hoary mustard

(continued)

Table 2 (continued)

Species name	Common name
Sinapis arvensis L.	Wild mustard, charlock
Sinapis alba L.	Yellow or white mustard
Raphanus sativus L.	Radish
Raphanus raphanistrum L.	Wild radish
Diplotaxis muralis (L.) DC.	Annual wall-rocket
Eruca strumgallicum (Willd.) O.E. Schulz	Dog mustard
Eruca vesicaria (L.) Cav. subsp. *sativa* (Mill.) Thell.	Rocket salad

Modified from OECD (2016)

Table 3 Heavy metal accumulation by *Brassica* and related genera

Heavy metal accumulated	Species name
Nickel (Ni)	*Alyssum lesbiacum*
	Astronidium inflatum
	Noccaea goesingensis
	B. juncea
Zinc (Zn)	*Arabidopsis halleri*
	Noccaea caerulescens
	B. napus
	B. rapa L.
Cadmium (Cd)	*B. juncea*
Chromium (Cr)	*B. juncea*
Copper (Cu)	*B. juncea*
Selenium (Se)	*B. oleracea* L.
	B. napus L.
Uranium (U)	*B. juncea*
	B. nigra (L.) Koch.
	Brassica chinensis L.
	Brassica narinosa L.
Lead (Pb)	*B. juncea*
	Brassica campetris L.
	B. carinata A. Br.
	B. napus L.
	B. nigra (L.) Koch.
Caesium (Cs)	*B. juncea*
	B. oleracea L.

Modified from Dar et al. (2015) and Pantola and Alam (2014)

Table 4 Arsenic content ($\mu g\ g^{-1}$) in root and shoot dry matter of Brassicaceae 12-days seedling stage (Freitas-Silva et al. 2016)

Species	As (μM)	Root ($\mu g\ g^{-1}$ DM)	Shoot ($\mu g\ g^{-1}$ DM)
B. oleracea	0	6.43	3.05
	250	17.66	3.64
	350	16.40	4.24
	450	24.86	7.20
B. juncea	0	7.45	1.58
	250 350	12.96 20.53	2.75 1.82
	450	25.35	2.69
R. sativus	0	3.85	1.49
	250	4.68	3.51
	350	6.73	3.85
	450	15.28	4.45

the element in the leaves into the reproductive organs of the plants; some reports are also there relating the volatilization of Se from leaves directly into the atmosphere. Accumulation of selenium by *S. pinnata* in the reproductive parts (flowers and seeds) is also being confirmed in a number of field studies with corresponding decrease in the leaf system (Galeas et al. 2007). Although *B. juncea* can also accumulate selenium but they basically prefer soils with moderate levels of Se; on the other hand, *Stanleya pinnata* can take up high amount of selenium even under soils with low amount of selenium (Terry et al. 2000).

6 Zinc (Zinc) Tolerance of *Arabidopsis halleri*

Arabidopsis halleri (syn: *Cardaminopsis halleri*) can tolerate higher concentrations of heavy metals (Brooks 1998). Zinc tolerance was investigated in five populations of *A. halleri* (syn.: *C. halleri*). All these were raised from the seeds collected from the even sites, i.e. both contaminated and uncontaminated. Irrespective of the origin, *A. halleri* seedlings showed a continuous growth of roots at 100 μM Zn, with no toxic symptoms (dry or chlorotic leaves) in the plants. In contrast to *A. halleri*, roots of other species like *Arabidopsis thaliana* and *Arabidopsis lyrata* subsp. *petraea* seedlings were completely repressed at 100 μMZn concentration (Bert et al. 2000). This study was the first to demonstrate the ability of *A. halleri* to tolerate high level of zinc in the soil. Even, uncontaminated site seedlings showed a tolerance suggested a constitutive trait in *A. halleri*.

Table 5 Nickel concentration in the roots of various species of Brassicaceae

Species	Treatments		
	Control	1 mM Ni	2 mM Ni
A. alyssoides	13.5	132	197
A. campestre	3.21	75.2	123
A. murale	128	816	1014
E. ibericum	7.15	146	386

Adopted from Drozdova et al. (2017)

7 Ni Tolerance of Brassicaceae Species

With an idea to identify potential accumulators, Drozdova et al. (2017) conducted a comparative study and reported the outcome of higher doses of Nickel on few wild growing plant species of Brassicaceae. Results of the experiments revealed distinct differences in the species in terms of tolerance to Ni. There were clear symptoms like chlorosis and necrosis on the leaves of species which are non-hyperaccumulators. After 11 days of Ni exposure, about 80% of plants *Alyssum alyssoides* and *Alyssum campestre* and 50% *Erysimum ibericum* started showing the toxicity symptoms. Surprisingly, *Alyssum murale* developed normally even in the same concentrations of Ni applied for *A. alyssoides*, *A. campestre*a nd *E. ibericum.* A comparative study of the accumulation of Ni is shown in Table 5. The accumulation of Ni was highest in the roots of *A. murale* suggesting its high efficiency of extracting Ni ions from the soil solution, even in areas with low Ni content. In terms of tolerance to high concentrations of Ni, the species could be arranged in the order: *A. murale* > *E. ibericum* > *A. alyssoides* > *A. campestre.*

8 Conclusion

Across many studies, it has been confirmed that the family Brassicaceae is remarkably vital for remediation of heavy metals and metalloids across the world. Brassicaceae comprises a number of species with better accumulation efficiency signifying a great tolerance level to metals. Although a number of species are identified with proper scientific theories on the mechanisms leading to the tolerance or hyperaccumulation; but their genetic level study linking with their metal tolerance ability needs to be explored for better understanding.

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