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BASIS FOR THE BREEDING OF LOW-Cd WHEAT VARIETIES

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Among heavy metals, cadmium (Cd) is highly toxic to plants and it is even considered as one of the most toxic elements released into environments at very low concentrations. The development of industry and agriculture have led to the increase of Cd content in soil environment. Cd is released into the soil through application of phosphate fertilizer, animal manures, waste water etc. Cadmium is a non-essential element for plant nutrition but because of its strong toxicity can seriously affects crop growth and development. Due to the high mobility of Cd in soil, the concentration of this element above the critical level can strongly inhibit the growth of plants as well as damage cell structure by interfering with different biochemical and physiological processes. Accumulation of Cd to phytotoxic levels may cause significant growth and yield decrease. If plants are grown in soil contaminated with Cd, they produce products containing this heavy metal, and such plant products are the main source of Cd entering the human body through the trophic chains. Thus, Cd may be an element with high residue, difficult to degrade and easy to accumulate, which may seriously threaten the health of human beings and animals. Cereals such as wheat, rice and maize are the main food crops in the world. Among them, wheat is the source of staple food for more than half of the world's population. Compared with other heavy metals, cadmium is more easily absorbed and accumulated by wheat. This poses a serious threat to human health. Wheat products are the main source of Cd intake by human. Wheat mainly uptakes Cd through the root system, and then it migrates to the above-ground part, and finally accumulates in the wheat grain. Agronomic management practices have been used to reduce Cd uptake and toxicity in wheat. However, these measures could pose some problems, such as large investment, high energy consumption, difficult operation and easy to produce secondary pollution. Low-Cd wheat varieties are the most effective and economic way to reduce the risk of cadmium to human health associated with food consumption. In the traditional breeding process, the selection of Cd-tolerant wheat samples is carried out on the basis of morphological, physiological or biochemical characteristics associated with Cd stress. It is of great significance to study the molecular mechanism of Cd absorption, transport of wheat and the creation of wheat varieties with low Cd accumulation for ensuring food security and food safety. Using molecular breeding technology and their successful integration with traditional breeding methods to select crop varieties with low accumulation of Cd will have a potential impact on the development of low Cd wheat germplasm and important practical significance for ensuring safe agricultural production of Cd contaminated soil. The objective of the present review is to discuss the Cd impact on wheat growth and development, Cd toxicity and tolerance mechanisms and some possible breeding strategies to alleviate Cd toxicity in wheat. The paper reviewed the effects of cadmium on the growth and development of wheat, the absorption, transport and distribution of cadmium in wheat, the tolerance mechanism and the molecular biological level of cadmium in wheat plant. To provide strategies and possible schemes for breeding wheat varieties with low cadmium accumulation

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Introduction. Heavy metal polluted soils have been a serious problem to crop production worldwide (Adrees et al., 2015; Ali et al., 2015; Bedford, 2017; Clemens et al, 2013; Habiba et al., 2015; Rizwan et al., 2016). Among heavy metals, cadmium (Cd) is highly toxic to plants and even Cd is considered as one of the most toxic elements released into environments even at very low concentrations due to its non-essentiality nutrient element in living organisms (Ashrafzadeh, 2016; Irfan et al., 2013; Ok et al., 2011). The development of industry and agriculture have led to the increase of Cd content in agricultural soil environment (Gu Jiguang & Zhou Qixing, 2002; Irfan et al., 2013; Lim et al., 2013; Ma et al., 2020; Menglong Xu et al., 2020). Cd is released into the soil environment through application of phosphate fertilizer, animal manures, waste water and garbage from metal industry and cement industry, Cd-contaminated sludge and fertilizer (Ahmad et al., 2012; Jamali et al., 2009; Jiao et al., 2004; Lu & Tian, 2017; Ma et al., 2020; Menglong Xu et al., 2020, Xiu et al, 2020). Accumulation of Cd to phytotoxic levels in plants may cause growth disorders and yield loss.

Cadmium is characterized by a high degree of mobility in soil. Concentration of it above the critical level can hinder the plant metabolism and may cause cell death by interfering with various biochemical and physiological processes, such as decreased the intracellular space and chloroplasts, stimulated the production of reactive oxygen species (ROS), leading to cell membrane damage and destruction of cell organelles (Changaei et al., 2012; Dandan et al., 2011; Khan et al., 2007; Küpper et al., 2013; Mühling et al., 2003; Poghosyan et al., 2014). Plants growing in Cd-contaminated soil Cd-contaminated food is the main source of Cd entry to humans via the trophic chain. Thus, Cd may be an element with high residue, difficult to degrade and easy to accumulate, which may seriously threaten the health of human beings and animals. (Adrees et al., 2015; Bedford G., 2017; Benavides et al., 2005; Dai et al., 2012; Huang et al., 2008). Plants have various mechanisms to protect Cd uptake and accumulation in seeds including exclusion at root level, compartmentalization of Cd and formation of stress proteins (Aprile et al., 2019; Bhati et al., 2016; Caverzan et al., 2016; Ci et al., 2010; Clemens et al., 2013; Cuypers et al., 2011; DalCorso et. al., 2010; Dandan et al., 2011; Ranieri et al., 2005). Cadmium uptake, translocation and toxicity in plants is also affected by interaction with other mineral nutrients such as Si, Pb, Cu and Zn (Ahmad et al., 2012; Cakmak et al., 2010; Ding Y. F., & Zhu C., 2009; Liang et al., 2007; Li et al., 2020; Lim et al., 2012; Maqsood et al., 2009; Rains et al., 2006).

Cereal crops such as wheat, rice and maize are the main food crops in the world. Among them, wheat is the source of staple food for more than half of the world's population, and the annual world output is about 650 million tons. In other words, wheat food is the main source of Cd intake by human. Compared with other cereals, wheat mainly accumulates Cd through the root system, and migrates to the above-ground part, and finally accumulates in the wheat grain (Chan & Hale, 2004; Hart et al., 2006; Jiang et al., 2004; Kubo et al., 2011). Lopez-Luna J. (2016) reported that Cd is more toxic to wheat than other toxic metals. Cd toxicity reduces the absorption and transport of essential elements in wheat. The root growth and morphology of wheat is seriously affected, resulting in the decrease of plant growth, biomass and grain yield (Black et al., 2014; Ci et al., 2010; Harris et al., 2004; Jiang et al., 2004; Kubo et al., 2011; Lin et al., 2007; Liu et al., 2015; Ranieri et al., 2005; Rizwan et al., 2016; Shafi et al., 2009; Sugiyama et al., 2007; Yourtchi & Bayat, 2014).

The problem must be confronted with reducing Cd-contaminated to be solved urgently. In recent years, agronomic management practices including plant growth regulators (PGRs), mineral nutrients, biochar, fertilizers, compost, crop rotation, cropping patterns, and microorganisms have been used to reduce Cd uptake and toxicity in wheat.(Abbas et al., 2017; Bashir et al., 2020; Khedr et al., 2019; Rehman et al., 2018; Wiebe et al., 2013). However, these measures could pose some problems, such as large investment, high energy consumption, difficult operation and easy to produce secondary pollution. (Gondor et al., 2014).

Therefore, it is very important to study the molecular mechanism of absorption, transport and efflux of Cd from wheat and to develop wheat varieties with low Cd accumulation to ensure food safety.

The objective of the present review is to discuss the Cd influence on wheat growth and development, Cd toxicity and tolerance mechanisms and some possible breeding strategies to alleviate Cd toxicity in wheat.

1. Effects of Cd on growth and development of winter wheat plants

1.1. Effects on seed germination and seedling growth of winter wheat

The seed germination and seedling stage are the beginning of plant life cycle. The first organ that comes into contact with Cd in soil is the seed. Therefore, seed germination is the earliest stage to perceive Cd toxicity. In general, low concentration of Cd has little inhibitory effect on seed germination, and even promotes germination of some wheat varieties. With the increase of treatment concentration, Cd had a very strong negative effect on seed germination, which was inhibiting the growth of shoot and root system of wheat seedlings, and the accumulation of dry matter also decreased. (Zhang et al., 2002). The study showed that the treatment concentration of 0.03 mg/kg Cd promoted the growth and dry matter accumulation of wheat. When the concentration of Cd was over 0.03 mg/kg, the growth and dry matter accumulation of wheat were extremely reduced (Zhang et al., 2002). The accumulation of Cd near the growing point of radicle leads to the inhibition of amylase activity and starch hydrolysis in wheat cotyledon. As a result, the nutrients required for the growth of radicle and hypocotyl are not satisfied and the elongation is inhibited. Sfaxi-Bousbih A. (2010) reported that the transport of mineral elements and carbohydrates from cotyledon to cotyledon and radicle of soybean was inhibited, which affected the germination and growth of seeds.

1.2. Effects of Cd on the growth of plant organs

Cd toxicity increases with the increase of concentration. Within a certain range of concentration, Cd can promote the growth of some plants. However, with the increase of Cd concentration, the growth and development of plants are significantly inhibited by Cd, which is generally manifested as short stature of plants, dechlorination of leaves, slow growth and decline of biomass. Cd affects plant photosynthesis, membrane system, enzyme system in vivo and metabolism related to the physiological activities, which eventually show a decline in growth and yield (Amirjani et. al., 2012; Dandan et al., 2011; Huang et al., 2008; Katashi et al., 2017; Khan et al., 2007; Lin et al., 2007; Song&Wang, 2017).

Under Cd toxicity, the reoperation amount and reoperation rate of pre-flowering storage substances in wheat leaves and other vegetative organs were significantly reduced, and the thousand seed weight also decreased with the increase of treatment concentration. Cd toxicity inhibited the differentiation of reproductive organs during the period from young spike phase to heading, resulting in the caryatization and abortion. After heading stage, Cd toxicity interferes with and inhibits the synthesis and accumulation of chlorophyll, soluble sugar, soluble protein and starch in wheat flag leaves, and interferes with the migration and redistribution of nutrients in the wheat (Awan et al., 2019; Jafarnejadi et al., 2018; Khan et al., 2007).

2. Cd uptake, transport and distribution by wheat plant

2.1. Cd absorption by wheat plants

Cadmium is high toxic metal and it effects plant growth and development through a number of mechanisms including water nutritional balance and production of reactive oxygen species (Amirjani, 2012; Liu et al., 2015). Among soil factors, soil salinity could shift the soil-solution chemical equilibrium in favour of more soluble Cd compounds like $CdCl_2$ and $CdCl^+$ thereby enhancing its availability to plants (Li et al., 2014; Liu et al., 2007; Özkutlu & Kara, 2019). The lower adsorbing ability of these species to soil than free Cd^{2+} ions increases Cd mobility at the soil-root interface. Moreover, these complexes can enhance transport of Cd across plasma membrane which results in increased soil-plant transfer of Cd under salinity. It was shown that combined stress of NaCl and Cd caused higher plasma membrane permeability and enhanced production of oxygen radicals and H_2O_2 in comparison to Cd and NaCl treatments alone in wheat (Muhling & Lauchli, 2003; Shafi et al., 2009).

In general, Cd is absorbed into plants through the root system. It was studied that the absorption of Cd by wheat roots at low Cd concentration was an active absorption process, and the energy required for transport was provided by the hydrolysis of ATP produced in the metabolic process, which was mainly reflected in the highly selective absorption of ions and the energy consumption mechanism (Abedi & Mojiri, 2020). There are various carrier proteins in plant root system, and each ion combines with its corresponding carrier protein (transporter) to form ions. Carrier complexes that transport ions into cells by means of metabolic energy. At high Cd concentrations, Cd absorption is a passive process involving diffusion, ion exchange and chelation. There is a cationic exchange between the internal tissues of the root and the rhizosphere of plants containing cadmium. This part of the absorption of Cd can be without Cd solution desorption from the epidermal cell walls come down. The other part is combined into irreversible macromolecules, and then Cd is absorbed in the root surface. The longer combined into irreversible the higher the proportion of large molecules. The process of diffusion is the process of entering Cd into the cell through the cell wall and cell membrane, which is energy independent and depends on the difference in concentrations of the medium (Greger & Lofstedt, 2004; Huang et al., 2020; Page & Feller, 2015). Root exudates and a series of changes induced by root exudates also affect the uptake of Cd by wheat. The release of root metabolites affect the uptake of Cd in wheat by influencing pH and Cd availability.

In addition, it has been reported that the variation of Cd uptake in over ground part of wheat at different growth stages was as follows: the late growth period was larger than the early growth period, the growth flourishing period was larger than the slow growth period, and the reproductive growth period was larger than the vegetative growth period. The Cd absorption amount and rate jointing stage and heading stage were significantly higher than those in other periods. Cd absorption was significantly positively correlated with dry matter weight gain ($r = 0.91633$), and absorption rate was significantly positively correlated with dry matter weight gain ($r = 0.8003$) (Jiang et al., 2007).

2.2. Cd transport and distribution in wheat

The accumulation of Cd in wheat depends on the transport of Cd from root to stem, while the accumulation of Cd in seeds depends on the transport of Cd from root to stem and the direct transport of Cd from root to stem to grain through the transport of lignin and phloem. (Abedi & Mojiri, 2020; Harris &Taylor, 2004; Hart et al., 2006). Transpiration and root pressure provide the impetus for this process. Concentration of Cd in wheat grains is not determined by the concentration of Cd in xylem, but mainly by the ability of Cd to be transported from xylem to the phloem of the spike. (Abedi &Mojiri, 2020; Riesen &Feller, 2005). Cd could be transported from the applied leaves to other phloem reservoir organs, such as new leaves (Cakmak et al., 2000).

It was found that Cd was transported in the soybean xylem in the form of cationic complex. This may be because xylem has a large number of amino acids and organic acids, and the metal complex formed by its combination with metal ions can avoid the obstacles to the transport of positively charged metal caused by the strong cation exchange ability of xylem cells, thus making it easier to transport. (Cataldo et al., 1988). Citric acid, low molecular weight dicarboxylic anions and inorganic cations in xylem fluid flow can also affect the transport of Cd. Citric acid can promote the transport of Cd in xylem and reduce the transport of Cd out of xylem (Senden et al., 1990; Senden et al., 1995).

Cadmium entry to the plant is possible through the xylem via symplastic transport and through apoplastic transport under high exposure (Dong et al., 2019). The accumulation of Cd in the grain was mainly transported into the grain by the phloem of flag leaves. The Cd in the leaves and stems can be redistributed to the seeds and the Cd in the seeds hardly transports to other parts. It can be speculated that the transport of Cd may be related to the transport of photosynthetic products. The re-transport of Cd into grains is also related to other metal ions. For example, zinc inhibits the phloem loading and transport of Cd, thus reducing the transfer of Cd from phloem transport to grains. J. J. Hart observed that Cd transported to wheat seeds might be related to phloem-mediated Cd transport to the grain (Hart et al. 2006). The phloem is the key Cd transport into wheat seeds. In general cadmium easily reach plants via root uptake and translocation to stems and seeds because of its high mobility (Abedi & Mojiri, 2020).

Cadmium, as mentioned above, enters the plants first through the root system and it is transported to the shoots in an ionic form in the xylem and phloem over transporters and transpiration. Cadmium may cause a wide range of effects on plants, impacts plant metabolism and causes oxidative stress, nutrient uptake disbalance (Huang et al., 2020; Navarro-Leon et al., 2019). Cd can impact the antioxidant defense system of plant organism and induce the formation of reactive oxygen species (ROS), which causes oxidative stress in general, Cd is accumulated in roots or transported to stems, leaves, fruits and other organs after being absorbed by plant from the soil (Ullah Zaid Imdad et al., 2018). However, the accumulation of Cd in plants varies with different parts, varieties, ecotypes and species of the same species. In the same plant object, Cd accumulation caused by roots is usually higher than in stems, leaves, and grains. On the cell level Cd is mainly distributed in the plastids and in the cell wall, and some of it forms carbonate and phosphate precipitation. Leaf, root and stem are easily enriched with Cd in wheat plants, while lower Cd level in seeds is an immovable element, which accumulated more in senescent parts and could not be reused by other non-senescent organs. The filling period and jointing - heading period are the key periods for the control of Cd accumulation. At the early stage of filling, the accumulation of Cd in different organs of wheat is mainly higher in leaves than in stems, leaf sheaths and grains. The accumulated content of leaf in mature stage was higher than that of leaf sheath, grain and stem (Ullah Zaid Imdad et al., 2018).

3. Cd tolerance mechanisms in wheat plant

Under the stress of Cd, it can stimulate the antioxidant defense system of plants, remove O^{2-} and H_2O_2 generated under the stress of Cd, maintain the balance of reactive oxygen metabolism, and protect the membrane structure, so as to enable plants to endure, reduce or resist stress injury to a certain extent. Therefore, increasing antioxidant enzyme activity is one of the main mechanisms of tolerance to Cd in plants, including wheat (Muhling & Lauchli, 2003; Khan et al., 2007; Chen et al., 2010; Poghosyan et al., 2014). Antioxidant defense systems include enzymes such as superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and non-enzymes such as ascorbic acid (AsA) and glutathione (GSH). It was used the method of direct stress of Cd on wheat seeds during germination to study that the activities of superoxide dismutase (SOD) and peroxidase (POD) increased with the growth of concentration, and malondialdehyde (MDA) content and cell membrane permeability also showed an increasing trend. The activity of POD and CAT increased with the increase of stress intensity, which indicated that the protective enzyme system in wheat was changed, which was also the protective response of plants to the adverse environment (Song et al., 2017; Tran & Popova, 2013; Zhao, 2011; Wang et al., 2017). Under the stress of Cd, the function of reactive oxygen radical scavenging system in wheat was reduced, resulting in the accumulation of H_2O_2 in the cells and the decrease of APX and GR activity. Wu et al. (2002) extended their research showed that Cd stress lead to the sharp decline in barley seedling GSH content. It may be a GSH Cd detoxification in great quantities, such as GSH for plant chelating peptide (PC) synthetic substrates, or act as antioxidants in the body by removal of biological active oxygen free radicals and generate oxidized glutathione (GSSG), to show the content. Malondialdehyde (MDA) is one of the main products of membrane lipid peroxidation and its content is an important indicator of the degree or strength of membrane lipid peroxidation. It was showed that MDA content in functional leaves of barley increased under the treatment of Cd, and increased with the extension of the treatment time of Cd. In addition, when the concentration of Cd was higher than 0.1 mol, the stress of Cd would cause the lipid peroxidation in the leaves of barley overground, while the lipid peroxidation was alleviated after a certain period of treatment under the stress of low concentration Cd (Wu et al., 2003).

3.1. Marker-Quantitative trait loci (QTL) analysis for Cd tolerance in wheat

The application of molecular marker-assisted selection in breeding has been paid more and more attention. Early in 1999, it was feasible to identify soybean germplasm using marker-quantitative trait loci (QTL). Bai Yi Xiong (Bai et al., 2019) analyzed the genetic information of 113 barley materials by using QTL method. The development of molecular markers related to Cd accumulation capacity also has a certain basis. Major genes associated with Cd uptake and transport in *Arabidopsis thaliana* have been identified as ABC family (Chen, 2004; Gaillard et al., 2008), HMA family (Craciun et al., 2012; Grispen et al., 2011, Takahashi et al., 2012), Nramp family (Thomine et al., 2003), ZIP family (Barberon M et al., 2014). Understanding the genetic basis and gene composition of Cd absorption of wheat varieties can provide theoretical basis for breeding low Cd accumulation samples. ScOpc20 gene is a dominant marker associated with high Cd content, which is restricted in backcross breeding (Dobrikova et al., 2017; He & Mubeen, 2020; Pozniak, 2010; Rebekić & Lončari, 2016). K. Wiebe developed an EST derived marker (XBF474090) co-isolated from a gene variant of Cd absorbing trait in crops, which has been successfully transformed into co-dominant CAPS marker, USW47 (Wiebe et al., 2010). After digestion of PCR amplification products with restriction enzyme of Hpyl88 I, electrophoresis analysis showed that the marker could be used to detect two alleles of Cd absorption trait genes. About 96 wheat samples were successfully divided into low Cd absorption type or high Cd absorption type. Y.-Y. Kim isolated a TM20 gene from the cDNA library of a wheat root, which produced specific Cd (Cd (II) tolerance (Kim et al., 2008). These genes potentially related to Cd accumulation in wheat, which could be further developed to match molecular markers.

It is a new idea to use molecular marker technology to screen germplasm resources. Molecular markers are developed on the presence of abundant polymorphisms in genomic DNA. It is a new and reliable genetic marker that directly reflects the differences of biological individuals at the level of DNA. DNA molecular markers are not affected by the environment and development stage, and a large number of markers can greatly improve the effectiveness and reliability of cross breeding (He et al., 2020; Grant et al., 2008; Pozniak, 2010).

4. Breeding strategies and possible schemes for Cd low-accumulation winter wheat varieties

Currently the protection of Cd pollution is mainly in some aspects:

- the first: to start from soil treatment, the development of soil improver and Cd inhibitor (Abbas et al., 2017; Bashir et al., 2020);
- the second: to select and breed cultivars with low accumulation of Cd and adjust the overall planting structure (Ullah Zaid Imdad et al., 2018).

Cd pollution hazards can also be controlled through rational management of fields, control of contaminated areas and restricted planting and production. However, these measures could pose some problems, such as large investment, high energy consumption, difficult operation and easy to produce secondary pollution.

Low-Cd wheat varieties are the most effective and economic way to reduce the risk of cadmium to human health associated with food consumption (Shiyu et.al., 2017; Vitale et al., 2020). In the traditional selection process, the selection of Cd-tolerant wheat samples is carried out on the basis of morphological, physiological or biochemical characteristics associated with Cd stress. To improve the genetic background of wheat varieties with increased resistance to Cd, intraspecific crosses are usually developed among promising individuals, with subsequent selection in subsequent generations (Ullah Zaid Imdad et al., 2018).

For the analysis of the source material, selection methods such as mass selection, pure line and periodic selection methods can be effectively used to obtain wheat varieties with low Cd content. Advances in genetics and molecular biology have expanded the possibilities for many modern selection methods that ensure wheat stability to Cd.

There are two key molecular approaches for estimating Cd stress in wheat: marker-selected and genomic selection (Randhawa et al., 2013; Wen et al., 2013). Molecular breeding is a new way to select germplasm resources (Bhati et al., 2015; Bhati et al., 2016; Ren et al., 2018; Wiebe et al., 2010). Compared with conventional chemical analysis methods, molecular breeding does not produce secondary pollution and is the most effective and important mode to reduce the accumulation of Cd in agricultural products. Using molecular breeding technology and their successful integration with traditional breeding methods to select crop varieties with low accumulation of Cd will have a potential impact on the development of low Cd wheat germplasm and important practical significance for ensuring safe agricultural production of Cd contaminated soil.

5. Regulatory factors and genes involved in Cd stress response

MicroRNA (miRNA) is an important group of small RNA, which negatively regulates the expression of target genes after transcription by mediating the degradation or translation of target mRNA, and is a new type of expression regulator (Chen et al., 2004; Jian et al., 2018; Knox et al., 2009). Previous studies have found that these Cd-related miRNA can participate in the response to Cd stress through heavy metal transport, sulfur assimilation, antioxidant stress and auxin signal transduction pathways, and play an important role in the response process of plants to heavy metal stress (Dai et al., 2011; Ding et al., 2009; Mendoza-Soto, A. B. et al., 2012; Min Yang, Z. et al., 2013). For example, miR 159 and miR 67 exert effects through the A B C (ATP-binding cassette) type transporter and Nramp family (Natural Resistance-associated Macrophage Protein) of important proteins that regulate the transport of heavy metal ions respectively (Zhou et al., 2012). MicroRNA-395 is involved in the response to heavy metal Cd and Hg stress by participating in the regulation of sulfate-starved low affinity sulfate transporters and APS1, APS3 and APS4 genes (ATP sulphurylase, APS) (Min Yang, Z. et al., 2013); miR398 plays an important role in the stress response of Cd, Hg, Cu and other heavy metals by targeting two kinds of SOD, namely CSD1 and CSD2 in Cu and Zn superoxide dismutase (Cu, Zn superoxide dis-mutase, CSD) (Min Yang et al., 2013). MicroRNA is at the center of gene expression regulation. In recent years, with the development and application of high-throughput sequencing technology, more and more miRNA related to heavy metals in plants have been cloned and identified.

At present, most of the studies on Cd stress in wheat focus on the selection of varieties resistant to Cd and the physiological and biochemical aspects. With the deepening of the study on the mechanism of Cd accumulation, some genes involved in Cd transport have been discovered in arabidopsis, rice and other plants (Kim et al., 2008; Wang et al., 2006.) Natural resistance associated with macrophage protein (OsNARMP5) is a strongly expressed Cd and Mn transporter in the root of rice. The mutant of OsNARMP5 can significantly reduce the absorption of Cd by the root system of rice, thus reducing the content of Cd in the grain to below 3 % of the control. OsHMA3 of the p1b-atpase subgroup is a heavy metal ion pump mainly expressed in the root of rice, which is located on the vacuole membrane and mediated the enrichment of Cd in the vacuole of rice root cells.

The over-expressed plants can selectively reduce the accumulation of Cd in seeds. Low affinity cationic transport protein (LCT1) is a new transport protein cloned from wheat, which is mainly expressed in the root and leaf of wheat (Wang et al., 2019). After RNA interference with OsLCT1 gene in rice, there was no significant change in xylem mediated Cd translocation. However, phloem-mediated Cd translocation decreased significantly, and the content of Cd in seeds was reduced to half of the control, indicating that it may be involved in the process of Cd transport from xylem of large vascular bundles to phloem of dispersed small vascular bundles in stem nodes as well as the process of phloem-mediated Cd transport to grains.

The results showed that the study of the genes related to Cd stress played an important role in the development of new varieties of Cd tolerant crops, which laid a foundation for excavating and functional analysis of Cd stress related genes in wheat. Research in this direction provides insight into the screening of functional genes that respond to stress, which can be useful for analyzing and improving the resistance of crops to Cd stresses. Simultaneously, it opens up a new way of high speed, simple operation and low cost for further breeding high Cd tolerance wheat varieties, which is of great significance to improve the grain safety of wheat and promote the sustainable development of agricultural production.

Conclusion. Cd is one of the major inorganic contaminants in the environment. Its presence in the soil or atmosphere has been recognized as a serious threat to agriculture. It is a practical and feasible way to select wheat varieties with low accumulation of Cd to reduce the absorption and accumulation of Cd in crops and thus reduce the content of Cd in agricultural products. In summary, many important achievements have been reported on the injury of Cd to wheat and the tolerance mechanism of Cd to wheat.

However, the effect of Cd on the growth of wheat is very complex. Multiple benefits could be achieved by future critical research efforts including the following:

• More detailed studies are needed to have a better understanding of Cd toxicity in wheat at the molecular level.

• The process and mechanism of the uptake, transport and accumulation of Cd by plants should be clarified, and some of these processes should be artificially regulated to improve the tolerance of plants to Cd pollution or reduce the absorption of Cd.

• If the grain yield of wheat varieties with low Cd absorption is low in the planting process.

• Which genes are activated if wheat is subjected to Cd stress ? How these genes work together to synthesize resistant proteins, peptides, amino acids, reducing sugars, and more.

• How to define a physiological index as the standard to measure the resistance and non-resistance to Cd in wheat in many physiological and biochemical reactions ?

If the research in these aspects can achieve breakthrough results, it will be another breakthrough direction of soil pollution treatment and utilization.

References:

1. Adrees, M., Ali, S., Rizwan, M., Ibrahim, M., Abbas, F., Farid, M., & Bharwana, S. A. (2015). The effect of excess copper on growth and physiology of important food crops: a review. Environmental Science and Pollution Research, 22(11), 8148–8162. doi: 10.1007/s11356-015-4496-5

2. Ali, S., Bharwana, S. A., Rizwan, M., Farid, M., Kanwal, S., Ali, Q., & Khan, M. D. (2015). Fulvic acid mediates chromium (Cr) tolerance in wheat (Triticum aestivum L.) through lowering of Cr uptake and improved antioxidant defense system. Environmental Science and Pollution Research, 22(14), 10601–10609. doi: 10.1007/s11356-015-4271-7

3. Bedford, G. (2017). Environmental concentrations of cadmium in the Taranaki environment and implications for policy. In: Science and policy: nutrient management challenges for the next generation. (Eds L.D. Currie and M. J. Hedley). [Electronic resource]. Access mode: http://flrc.massey.ac.nz/publications.html. Occasional Report No. 30. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand, 7.

4. Clemens, S., Aarts, M.G.M., Thomine S. & Verbruggen, N. (2013). Plant science: The key to preventing low cadmium poisoning. Trends Plant Sci., 18(2), 92–99. doi: 10.1016/j.tplants.2012.08.003

5. Habiba, U., Ali, S., Farid, M., Shakoor, M. B., Rizwan, M., Ibrahim, M. & Ali, B. (2014). EDTA enhanced plant growth, antioxidant defense system, and phytoextraction of copper by *Brassica napus* L. Environmental Science and Pollution Research, 22(2),

1534–1544. doi: 10.1007/s11356-014-3431-5

6. Rizwan, M., Ali S., Abbas, T., Zia-Ur-Rehman, M., Hannan, F., Keller, C., Al-Wabel, M.I. & Ok, Y. S. (2016). Cadmium minimization in wheat: A critical review. Ecotoxicol Environ Saf., 130, 43–53. doi: 10.1016/j.ecoenv.2016.04.001

7. Ashrafzadeh, S., & Leung, D.W.M. (2016). Development of Cadmium-safe crop cultivars: A Mini Review. J. Crop Improv., 30, 107–117. doi: 10.3390/agronomy8110249

8. Irfan, M., Hayat, S., Ahmad, A., & Alyemeni, M. N. (2013). Soil cadmium enrichment: Allocation and plant physiological manifestations. Saudi J. Biol. Sci., 20, 1–10. doi: 10.1016/j.sjbs.2012.11.004

9. Ok, Y. S., Usman, A. R. A., Lee, S. S., Abd El-Azeem, S. A. M., Choi, B., Hashimoto, Y. & Yang, J. E. (2011). Effects of rapeseed residue on lead and cadmium availability and uptake by rice plants in heavy metal contaminated paddy soil. Chemosphere, 85(4), 677–682. doi: 10.1016/j.chemosphere.2011.06.073

10. Gu, Jiguang & Zhou, Qixing (2002). Management and phytoremediation of cadmium contaminated soil. Ecological science, 21(4), 352–356. doi: 10.4172/2155-6199.1000376

11. Lim, J. E., Ahmad, M., Usman, A. R. A., Lee, S. S., Jeon, W. T., Oh, S.-E., & Ok, Y. S. (2012). Effects of natural and calcined poultry waste on Cd, Pb and As mobility in contaminated soil. Environmental Earth Sciences, 69(1), 11–20. doi: 10.1007/s12665-012-1929-z

12. Ma, J., Chen, Y., Antoniadis, V, Wang, K., Huang, Y., & Tian, H. (2020). Assessment of heavy metal(loid)s contamination risk and grain nutritional quality in organic waste-amended soil. Journal of Hazardous Materials, 399, 23095. doi: 10.1016/j.jhazmat.2020.123095

13. Menglong, X., Yazi, L. Y., Yan, D., Siyuan , Z., Xiaodong, H., Ping, Z., Jieyi, Z., Huaqun, Y., Yili, L., Hongwei, L., Xueduan, L., Lianyang, B., Luhua, J. & Huidan, J. (2020). Bioremediation of cadmium-contaminated paddy soil using an autotrophic and heterotrophic mixture. Electronic Supplementary Material (ESI) for RSC Advances. J. Royal Society of Chemistry, 44. doi: 10.1039/d0ra03935g

14. Chen, X., Liu, Y. M., Zhao, Q. Y., Cao, W.Q., Chen, X. P., & Zou, C.Q. (2020). Health risk assessment associated with heavy metal accumulation in wheat after long-term phosphorus fertilizer application. Environmental Pollution, 262, 114348. doi: 10.1016/j.envpol.2020.114348

15. Ahmad, M., Usman, A. R. A., Lee, S. S., Kim, S.-C., Joo, J. H., Yang, J. E., & Ok, Y. S. (2012). Eggshell and coral wastes as low cost sorbents for the removal of Pb^{2+}, Cd^{2+} and Cu^{2+} from aqueous solutions. Journal of Industrial and Engineering Chemistry, 18(1), 198–204.

16. Jamali, M. K., Kazi, T. G., Arain, M. B., Afridi, H. I., Jalbani, N., Kandhro, G.A., Shahand, A. Q., & Baig, J. A. (2009). Heavy metal accumulation in different varieties of wheat (*Triticum aestivum* L.) grown in soil amended with domestic sewage sludge, J. Hazard. Mater. 164(2–3), 1386–1391. doi: 10.1016/j.jhazmat.2008.09.056

17. Jiao, Y., Grant, C.A., & Bailey, L.D. (2004). Effects of phosphorus and zinc fertilizer on cadmium uptake and distribution in flax and durum wheat. J. Sci. Food Agric., 84, 777–785. doi: 10.1002/jsfa.1648

18. Lu, C. & Tian, H. (2017). Global nitrogen and phosphorus fertilizer use for agriculture production in the past half century: Shifted hot spots and nutrient imbalance. Earth Syst. Sci. Data, 9, 1–33. doi:10.5194/essd-9-181-2017

19. Changaei, N. H., Sharifabad, H., Paknejad, F., Ardakani, M. R. & Hamidi A. (2012). Variation in antioxidant enzymes of 11 wheat cultivars from Iran. Annals Biol. Res., 3(6), 3026–3028.

20. Dandan, L., Dongmei, Z., Peng, W., Nanyan, W. & Xiangdong, Z. (2011). Subcellular Cd distribution and its correlation with antioxidant enzyme activities in wheat (*Triticum aestivum*) roots. Ecotoxicol. Environ. Safety, 74, 874–881. doi: http://10.1016/j.ecoenv.2010.12.006

21. Khan, N. A., Singh, S., & Nazar, R. (2007). Activities of antioxidative enzymes, sulp hurassimilation, photosynthetic activity and growth of wheat (*Triticum aestivum*) cultivars differing in yield potential under cadmium stress. J. Agron. Crop Sci., 193, 435–444. doi: 10.1626/pps.14.148

22. Küpper, H., & Leitenmaier, B. (2013). Cadmium-accumulating plants. Met Ions Life Sci.,11,373–393. doi: 10.1007/978-94-007-5179-8_12.

23. Mühling, K. H., & Läuchli, A. (2003). Interaction of NaCl and Cd stress on compartmentation pattern of cations, antioxidant enzymes and proteins in leaves of two wheat genotypes differing in salt tolerance. Plant Soil, 253, 219–231.

24. Abbas, T., Rizwan, M., Ali, S., Zia-Ur-Rehman, M., Qayyum, M. F., Abbas, F., Hannan, F., Rinklebe, J., & Ok, Y. S. (2017). Effect of biochar on cadmium bioavailability and uptake in wheat (*Triticum aestivum* L.) grown in a soil with aged contamination. Ecotoxicol. Environ. Saf., 140, 37–47. doi: 10.1016/j.ecoenv.2017.02.028

25. Poghosyan, G. H., Mukhaelyan, Zh., H., & Vardevanyan, P. H. Influence of cadmium ions on growth and antioxidant system activity of wheat (Triticum Aestivum L.) (2014). Seedlings, International Journal of Scientific Research in Environmental Sciences, 10, 2, 371–378. doi: 10.12983/ijsres-2014-p0371-0378

26. Benavides, M. P., Gallego, S. M., & Tomaro, M. L. (2005) Cadmium toxicity in plants. Brazilian Journal of Plant Physiology, 17(1), 21–34. doi: 10.1590/S1677-04202005000100003

27. Dai, X. P., Feng, L., Ma, X. W., & Zhang, Y. M. (2012). Concentration level of heavy metals in wheat grains and the health risk Assessment to local inhabitants from Baiyin, Gansu, China. Advanced Materials Research, 518(523), 951–956. doi: 10.4028/www.scientific.net/amr.518-523.951

28. Huang, M., Zhou, S., Sun, B., & Zhao, Q. (2008). Heavy metals in wheat grain: Assessment of potential health risk for inhabitants in Kunshan, China. Science of The Total Environment, 405(1–3), 54–61. doi: 10.1016/j.scitotenv.2008.07.004

29. Aprile, A., Sabella, E., Francia, E., Milc, J., Ronga, D., Pecchioni, N., Ferrari, E., Luvisi, A., Vergine, M., & Bellis, L. D. (2019). Combined effect of cadmium and lead on durum wheat. Int. J. Mol. Sci., 20, 5891. doi: 10.1186/s12870-018-1473-4

30. Bhati, K. K., Alok, A., Kumar, A., Kaur, J., Tiwari, S., & Pandey, A. K. (2016). Silencing of ABCC13 transporter in wheat reveals its involvement in grain development, phytic acid accumulation and lateral root formation. J. Exp.Bot., 67, 4379–4389. doi: 10.1093/jxb/erw224

31. Caverzan, A., Casassola, A., & Brammer, S. P. (2016). Antioxidant responses of wheat plants under stress. Genet Mol Biol., 39(1), 1–6. doi: 10.1590/1678-4685-GMB-2015-0109

32. Ci ,W., Jiang, D., Wollenweber, B., Dai, T., Jing, Q. & Cao, W. (2010). Cadmium stress in wheat seedlings: growth, cadmium accumulation and photosynthesis. Acta Physiologiae Plantarum, 32(2), 365–373. doi: 10.1007/s11738-009-0414-0

33. Cuypers, A., Smeets, K., Ruytinx, J., Opdenakker, K., Keunen, E., Remans, T., Horemans, N., Vanhoudt, N., Van Sanden, S., Van Belleghem, F., Guisez, Y., Colpaert, J., & Vangronsveld, J. (2011). The cellular redox state as a modulator in cadmium and copper responses in Arabidopsis thaliana seedlings. J. Plant Physiol., 168, 309–316. doi :10.1016/j.jplph.2010.07.010

34. DalCorso, G., Farinati, S., & Furini, A. (2010). Regulatory networks of cadmium stress in plants. Plant Signal. Behav., 5, 663–667. doi: 10.4161/psb.5.6.11425

35. Ranieri, A., Castagna, A., Scebba, F., Careri, M., Zagnoni, I., Predieri, G., Pagliari, M., & di Toppi, L. S. (2005). Oxidative stress and phytochelatin characterisation in bread wheat exposed to cadmium excess. Plant Physiol. Biochem., 43, 45–54. doi: 10.1016/j.plaphy.2004.12.004.

36. Cakmak, I., Welch, R. M., Erenoglu, B., Römheld, V., Norvell, W. A., & Kochian, L. V. (2000). Influence of varied zinc supply on re-translocation of cadmium (109cd) and rubidium (86rb) applied on mature leaf of durum wheat seedlings. Plant and Soil, 219(1-2), 279-284. doi: 10.1023/A:1004777631452

37. Ding, Y. F. & Zhu, C. (2009). The role of micrornas in copper and cadmium homeostasis. Biochemical and Biophysical Research Communications, 386(1), 6–10. doi: 10.1016/j.bbrc.2009.05.137

38. Li, L., Zhang, Y., Ippolito, J. A., Xing, W., Qiu, K. & Wang, Y. (2020). Cadmium foliar application affects wheat Cd, Cu, Pb and Zn accumulation. Environmental Pollution (Barking, Essex:1987), 262, 114329. doi: 10.1016/j.envpol.2020.114329.

39. Maqsood, M. A., Rahmatullah, S., Kanwal, T. Aziz & Ashraf, M. (2009). Evaluation of Zn distribution among grain and straw of twelve indigenous wheat *(Triticum aestivum* L.) genotypes. Pak. J. Bot., 41(1), 225–231.

40. Rains, D. W., E. Epstein, Zasoski, R. J. & Aslam, M. (2006). Active silicon uptake by wheat. Plant Soil, 280, 223–228. doi: 10.1007/s11104-005-3082-x

41. Chan, D. Y. & Hale, B. A. (2004). Differential accumulation of Cd in durum wheat cultivars: uptake and re-translocation as sources of variation. J. Exp. Bot., 55, 2571–2579. doi: 10.1093/jxb/erh255

42. Hart, J. J., Welch, R. M., Norvel, W. A. & Kochian, L. V. (2006). Characterization of cadmium uptake, translocation and storage in near-isogenic lines of durum wheat that differ in grain cadmium concentration. New Phytologist., 172, 261–271. doi: 10.1111/j.1469-8137.2006.01832.x

43. Jiang, L., Shao, Y., Li, C X, Li, X. L., Lu, X.Y, & Ma, S. C. (2004). Study on the absorption, distribution and accumulation of cadmium in wheat plants. Henan agricultural sciences, 33(7), 13–17. (in Chinese with English abstract)

44. Kubo, K., Watanabe Y., Matsunaka, H., Seki, M., Fujita, M., Kawada, N., Hatta, K., & Nakajima, T. (2011). Differences in cadmium accumulation and root morphology in seedlings of Japanese wheat varieties with distinctive grain cadmium concentration. Plant Production Sci., 14, 148–155. doi: 10.1626/pps.14.148

45. López-Luna, Jaime, Silva-Silva, M. J., Martinez-Vargas, Sergio, Mijangos-Ricárdez, Oscar, Gonzalez, Chavez, Ma del, Carmen; Solís-Domínguez, F.A. & Cuevas-Díaz, M. C. (2016). Magnetite nanoparticle (NP) uptake by wheat plants and its effect on cadmium and chromium toxicological behavior. Science of The Total Environment, 565. doi: 10.1016/j.scitotenv.2016.01.029

46. Black, A., McLaren, R. G., Speir, T. W., Clucas, L. & Condron, L. M. (2014). Gradient differences in soil metal solubility and uptake by shoots and roots of wheat (*T. aestivum*). Biol. Fertil. Soils., 50, 685–694. doi: 10.1007/s00374-013-0886-3

47. Ci, D., Jiang, D., Dai, T., Jing, Q. & Cao, W. (2009). Effects of cadmium on plant growth and physiological traits in contrast wheat recombinant inbred lines differing in cadmium tolerance. Chemosphere, 77, 1620–1625. doi: 10.1016/j.chemosphere.2009.08.062

48. Harris, N. J. & Taylor, G. J. (2004). Cadmium uptake and translocation in seedlings of near isogenic lines of durum wheat that differ in grain cadmium accumulation. BMC Plant Biol., 4, 4–15. doi: 10.1186/1471-2229-4-4

49. Lin, R., Wang, X., Luo, Y., Du, W., Guo, H., & Yin, D. (2007). Effects of soil cadmium on growth, oxidative stress and antioxidant system in wheat seedlings (*Triticum aestivum* L.). Chemosphere, 69, 89–98. doi: 10.1016/j.chemosphere.2007.04.041

50. Liu, K., He, L.V. J., Zhang, W., Cao, H. & Dai, Y. (2015). Major factors influencing cadmium uptake from the soil into wheat plants. Ecotoxicology and Environmental Safety, 113, 207–213.

51. Rizwan, M., Meunier, J.-D., Davidian, J.-C., Pokrovsky, O., Bovet, N., & Keller, C. (2016). Silicon alleviates Cd stress of wheat seedlings (Triticum turgidum L. cv. Claudio) grown in hydroponics. Environ. Sci. Pollut. Res., 23, 1414–1427. doi: 10.1007/s11356-015-5351-4.

52. Shafi, M., Bakht, J., Hassan, M. J., Raziuddin, M. & Zhang, G. (2009). Effect of cadmium and salinity stresses on growth and antioxidant enzyme activities of wheat (*Triticum aestivum* L.). Bull Environ. Contam. Toxicol., 82, 772–776. doi: 10.1007/s00128-009-9707-7

53. Sugiyama, M., Ae, N. & Arao, T. (2007). Accumulation of large amounts of Cd in the root may limit the accumulation of Cd in edible above-ground portions of the plant. Plant Soil, 295, 1–11. doi: 10.3390/ijerph13030289

54. Yourtchi, M. S., & Bayat, H. (2014). Effect of cadmium toxicity on growth, cadmium accumulation and macronutrient content

of durum wheat (Dena CV.). Middle East Journal of Applied Sciences, 4(4), 1110–1117.

55. Bashir, A., Rizwan, M., Rehman, M.Z.U., Zubair, M., Riaz, M., Qayyum, M. F., Alharby, H. F., Bamagoos, A. A., & Ali, S. (2020). Application of co-composted farm manure and biochar increased the wheat growth and decreased cadmium accumulation in plants under different water regimes. Chemosphere, 246, 125809. doi: 10.1016/j.chemosphere.2019.125809

56. Khedr, M. E., Nasseem, M. G., Ali, W. H., & Rashad, M. A. (2019). Compost and vermicompost as soil amendments to immobilize Cu and Cd under wheat growth conditions. Alex. Sci. Exch. J., 40, 705–716. doi: 10.21608/ASEJAIQJSAE.2019.68390

57. Rehman, M.Z.U.; Rizwan, M.; Hussain, A.; Saqib, M.; Ali, S.; Sohail, M. I.; Shafiq, M. & Hafeez, F. (2018). Alleviation of cadmium (Cd) toxicity and minimizing its uptake in wheat (Triticum aestivum) by using organic carbon sources in Cd-spiked soil. Environ. Pollut., 241, 557–565. doi: 10.1016/j.envpol.2018.06.005

58. Wiebe, K., Harris, M. S., Faris, J. D., Clarke, J. M., Knox, R. E., Taylor, G. J., & Xiao, Chunwen, Luo, Xiuyun, Tian, Yun, & Lu, Xiangyang. (2013). Research progress on bioremediation of heavy metal cadmium pollution. Chemical and biological engineering, 30(8), 1–4. doi: 10.11707/j.1001-7488.20170517

59. Gondor, O.K., Szalai, G., Kovács, V., Janda, T., & Pál, M. (2014). Impact of UV-B on drought-or cadmium-induced changes in the fatty acid composition of membrane lipid fractions in wheat. Ecotoxicol. Environ. Saf., 108, 129–134. doi: 10.1016/j.ecoenv.2014.07.002

60. Zhang, G., Fukami, M. & Sekimoto, H. (2002). Difference between two wheat cultivars in Cd and mineral nutrient uptake under different Cd levels. Chinese Journal of Applied Ecology, 4, 454–458.

61. Sfaxi-Bousbih, A., Chaoui, A. & El Ferjani, E. (2010). Cadmium impairs mineral and carbohydrate mobilization during the germination of bean seeds. Ecotoxicology and Environmental Safety, 73(6), 1123–1129. doi: 10.1016/j.ecoenv.2010.01.005.

62. Huang, X., Duan, S., Wu, Q., Yu, M., & Shabala, S. (2020). Reducing Cadmium accumulation in plants: structure–function relations and tissue-specific operation of transporters in the spotlight. Plants, 9, 223. doi: 10.3390/plants9020223

63. Kubo, K., Kobayashi, H., Fujita, M., Ota, T., Minamiyama, Y., Watanabe,Y., Nakajima, T., & Shinano, T. (2016). Varietal differences in the absorption and partitioning of cadmium in common wheat (*Triticum aestivum* L.). Environmental and Experimental Botany, 124(79). doi: 10.1016/j.envexpbot.2015.12.007

64. Song, Y.; Jin, L.; & Wang, X. (2017). Cadmium absorption and transportation pathways in plants. Int. J. Phytoremediat., 19, 133–141. doi: 10.1080/15226514.2016.1207598

65. Jafarnejadi, A., Shokohfar, A., & Panahpoor, E. (2018). Evaluation of Cd Concentration in Wheat Crop Affected by Cropping System. Jundishapur Journal of Health Sciences. doi: 10.5812/jjhs.14400

66 .Amirjani, M. R. (2012). Effects of cadmium on wheat growth and some physiological factors. Intl. J. Forest, Soil and Erosion., 22(1), 50–58.

67. Li, Y., Wang, L., Yang, L. & Li, H. (2014). Dynamics of rhizosphere properties and antioxidative responses in wheat under cadmium stress. Ecotoxicology and Environmental Safe, 102, 55–61.

68. Liu, Q., Tjoa, A., & Römheld, V. (2007). Effects of chloride and co-contaminated zinc on cadmium accumulation. Bull. of Environment Cont. and Toxicol., 79(1), 62–65.

69. Özkutlu, F. & Kara, Ş. (2019). Cd concentration of durum wheat grain as influenced by soil salinity. Akademik Ziraat Dergisi., 97-100. doi: 10.29278/azd.593833

70. Shafi, M., Bakht, J., Guoping, Z., Din, M. R., Islam, E., & M. Aman. (2010). Effect of cadmium and salinity stresses on root morphology of wheat. Pak. J. Bot., 42, 2747–2754.

71. Abedi, T., & Mojiri, A. (2020) Cadmium uptake by wheat (*Triticum aestivum* L.): An Overview. Plants., 9, 500. doi: 10.3390/plants9040500

72. Greger, M. & Lofstedt, M. (2004). Comparison of uptake and distribution of cadmium in different cultivars of bread and durum wheat. Crop Sci., 44, 501–507 doi: 10.2135/cropsci2004.5010

73. Riesen, O.& Feller, U. (2005). Redistribution of nickel, cobalt, manganese, zinc, and cadmium via the phloem in young and maturing wheat. J. plant Nutr., 28, 421–430. doi: 10.1081/PLN-200049153

74. Page, V., & Feller, U. (2015). Heavy Metals in Crop Plants: Transport and Redistribution Processes on the Whole Plant Level. Agronomy. 2015, 5, 447–463. doi: 10.3390/agronomy503044

75. Cataldo, D. A., McFadden, K. M., Garland, T. R., & Wildung, R. E. (1988). Organic constituents and complexation of Nickel(II), Iron(III), Cadmium(II), and plutonium(IV) in soybean xylem exudates. Plant Physiology, 86(3), 734–739. doi: 10.1104/pp.86.3.734

76. Senden, M. H. M. N., Vand der Meer, A.J.G.M., Verburg, T. G., & Woltetbeek, H. T. (1994). Effects of cadmium on the behaviour of citric acid in isolated tomato xylem cell walls. Journal of Experimental Botany, 45(5), 597–606. doi: 10.1093/jxb/45.5.597)

77. Senden, M. H. M. N., Vand der Meer, A. J. G. M., Verburg ,T. G., & Wolterbeek, H. T. (1995). Citric acid in tomato plant roots and its effect on cadmium uptake and distribution. Plant and Soil, 171 (2), 333–339. [Electronic resource]. Access mode: https://link.springer.com/article/10.1007/BF00010289)

78. Dong, Q., Fangm, J., Huang, F., & Cai, K. (2019). Silicon amendment reduces soil cd availability and cd uptake of two pennisetum species. Int. J. Environ. Res. Public Health, 16, 1624. doi: 10.3390/ijerph16091624

79. Navarro-Leon, E.; Oviedo-Silva, J.; Ruiz, J.M., & Blasco, B. (2019). Possible role of HMA4a TILLING mutants of Brassica rapa in cadmium. Ecotoxicol. Environ. Saf., 180, 88–94. doi: 10.1016/j.ecoenv.2019.04.081

80. Ullah Zaid, Imdad & Zheng, Xin & Li, Xiaofang (2018). Breeding low-cadmium wheat: progress and perspectives. Agronomy, 8, 249. doi: 10.3390/agronomy8110249.

81. Tran, T. A. & Popova, L. P. (2013). Functions and toxicity of cadmium in plants: Recent advances and future prospects.

Turk. J. Bot., 37, 1–13. doi: 10.3906/bot-1112-16
82. Zhao, Y. (2011). Cadmium accumulation and antioxidant defence in leaves of *Triticum aestivum* L. and *Zea mays* L. African J. Biotechnol., 10(15), 2936–2943. doi: 10.5897/AJB10.1230
83. Wang, Z., Li, Q., Wu, W., Guo, J., & Yang, Y. (2017). Cadmium stress tolerance in wheat seedlings induced by ascorbic acid was mediated by NO signaling pathways. Ecotoxicol. Environ. Saf., 135, 75–81. doi: 10.1016/j.ecoenv.2016.09.013
84. Wu, F., Zhang, G., & Dominy, P. (2003). Four barley genotypes respond differently to cadmium: lipid peroxidation and activities of antioxidant capacity. Environmental and Experimental Botany, 50(1), 67–78. doi: 10.1016/S0098-8472(02)00113-2)
85. Bai, Yi Xiong, Zheng, Xue Qing,Yao, You Hua, Yao, Xiao Hua, & Wu, Kun Lun (2019). Genetic diversity analysis and comprehensive evaluation of phenotypic traits in hulless barley germplasm resources. Scientia Agricultura Sinica 52(23), 4201–4214. doi: 10.3864/j.issn.0578-1752.2019.23.002
86. Chen, X. (2004). A MicroRNA as a Translational Repressor of APETALA2 in Arabidopsis Flower Development. Science, 303(5666), 2022–2025. doi: 10.1126/science.1088060
87. Gaillard, S., Jacquet, H., Vavasseur, A., Leonhardt, N. & Forestier, C. (2008). AtMRP6/AtABCC6, an ATP-Binding cassette transporter gene expressed during early steps of seedling development and up-regulated by cadmium in *Arabidopsis thaliana.* BMC Plant Biol., 8(22). doi: 10.1186/1471-2229-8-22
88. Craciun, A. R., Meyer, C.-L., Chen, J., Roosens, N., De Groodt, R., Hilson, P., & Verbruggen, N. (2012). Variation in HMA4 gene copy number and expression among *Noccaea caerulescens* populations presenting different levels of Cd tolerance and accumulation. Journal of Experimental Botany, 63(11), 4179–4189. doi: 10.1093/jxb/ers104
89. Grispen, V. M. J., Hakvoort, H. W. J., Bliek, T., Verkleij, J. A. C., & Schat, H. (2011). Combined expression of the Arabidopsis metallothionein MT2b and the heavy metal transporting ATPase HMA4 enhances cadmium tolerance and the root to shoot translocation of cadmium and zinc in tobacco. Environmental and Experimental Botany, 72(1), 71–76. doi: 10.1016/j.envexpbot.2010.01.005
90.Takahashi, R., Ishimaru, Y., Shimo, H., Ogo, Y., Senoura, T., Nishizawa, N. K., & Nakanishi, H. (2012). The OsHMA2 transporter is involved in root-to-shoot translocation of Zn and Cd in rice. Plant, Cell & Environment, 35(11), 1948–1957.
91. Dobrikova, A. G., Yotsova, E. K., Borner, A., Landjeva, S. P. & Apostolova, E. L. (2017). The wheat mutant DELLA-encoding gene (Rht-B1c) affects plant photosynthetic responses to cadmium stress. Plant Physiol. Biochem., 114, 10–18. doi: 10.1016/j.plaphy.2017.02.015
92. Pozniak, C. J. (2010). Targeted mapping of Cdu1, a major locus regulating grain cadmium concentration in durum wheat (Triticum turgidum L. var durum). Theoretical and Applied Genetics, 121(6), 1047–1058. doi: http://10.1007/s00122-010-1370-1
93. Rebekić, A. & Lončarić, Z. (2016). Genotypic difference in cadmium effect on agronomic traits and grain zinc and iron concentration in winter wheat. Emir. J. Food Agric., 28, 772–778. doi: 10.9755/ejfa.2016-05-475.
94. He, C., Ding, Z., Mubeen, S., Guo, X., Fu Hi., & Xin, G. (2020). Evaluation of three wheat (*Triticum aestivum* L.) cultivars as sensitive Cd biomarkers during the seedling stage. Peerj.,8. doi: 10.7717/peerj.8478.
95. Thomine, S., Lelièvre, F., Debarbieux, E., Schroeder, J. I., & Barbier-Brygoo, H. (2003). AtNRAMP3, a multispecific vacuolar metal transporter involved in plant responses to iron deficiency. The Plant Journal, 34(5), 685–695. doi: 10.1046/j.1365-313x.2003.01760.x
96. Barberon, M., Dubeaux, G., Kolb, C., Isono, E., Zelazny, E., & Vert, G. (2014). Polarization of iron-regulated transporter 1 (irt1) to the plant-soil interface plays crucial role in metal homeostasis. Proceedings of the National Academy of Sciences, 111(22), 8293-8298. doi: 10.1073/pnas.1402262111
97. Kim, Y.-Y., Kim, D.-Y., Shim, D., Song, W.-Y., Lee, J., Schroeder, J. I., & Lee, Y. (2008). Expression of the novel wheat gene tm20 confers enhanced cadmium tolerance to bakers' yeast. Journal of Biological Chemistry, 283(23), 15893–15902. doi: 10.1074/jbc.M708947200
98. Grant, C. A., Clarke, J. M., Duguid, S., & Chaney, R. L. (2008). Selection and breeding of plant cultivars to minimize cadmium accumulation. Sci. Total Environ., 390(2–3), 301–310. doi: 10.1016/j.scitotenv.2007.10.038
99. Wang, S., Wu, W., Liu, F., Liao, R. & Yaqi, Hu. (2017). Accumulation of heavy metals in soil-crop systems: a review for wheat and corn. Environmental Science and Pollution Research, 24(2), 18, 15209–15225 .doi: 10.1007/s11356-017-8909-5
100. Vitale, J., Adam, B. & Vitale, P. (2020). Economics of wheat breeding strategies: focusing on oklahoma hard red winter wheat. Agronomy, 10, 238. doi: 10.3390/agronomy10020238
101. Randhawa, H. S., Asif, M., Pozniak, C., Clarke, J.M., Graf, R. J., Fox, S. L., Humphreys, D. G., Knox, R. E., DePauw, R. M. & Singh, A. K. (2013). Application of molecular markers to wheat breeding in Canada. Plant Breed., 132, 458–471.
102. Wen, W., Deng, Q., Jia, H., Wei, L., Wei, J., Wan, H., Yang, L., Cao, W. & Ma, Z. (2013). Sequence variations of the partially dominant DELLA gene Rht-B1c in wheat and their functional impacts. J. Exp. Bot., 64, 3299–3312. doi: 10.1093/jxb/ert183
103. Bhati, K. K., Aggarwal, S., Sharma, S., Mantri, S., Singh, S. P., Bhalla, S., Kaur, J., Tiwari, S., Roy, J. K., Tuli, R. & Pandey, A. K. (2014). Differential expression of structural genes for the late phase of phytic acid biosynthesis in developing seeds of wheat (Triticum aestivum L.). Plant Sci., 224, 74–85. doi: 10.1016/j.plantsci.2014.04.009
104. Bhati, K. K., Sharma, S., Aggarwal, S., Kaur, M., Shukla, V., Kaur, J., Mantri, S. & Pandey, A. K. (2015). Genome-wide identification and expression characterization of ABCC-MRP transporters in hexaploid wheat. Front. Plant Sci., 6, 488. doi: 10.3389/fpls.2015.00488
105. Ren, Y., Chen, Y., An, J., Zhao, Z., Zhang, G., Wang, Y., & Wang, W. (2018). Wheat expansin gene TaEXPA2 is involved in conferring plant tolerance to Cd toxicity. Plant Sci., 270, 245–256. doi: 10.1016/j.plantsci.2018.02.022
106. Jian, H., Yang, B., Zhang, A., Ma, J., Ding, Y., Chen, Z., Li, J., Xu, X. & Liu, L. (2018). Genome-Wide Identification of

MicroRNAs in Response to Cadmium Stress in Oilseed Rape (*Brassica napus* L.) Using High-Throughput Sequencing. Int. J. Mol. Science, 19, 1431. doi: 10.3390/ijms19051431

107. Knox, R. E., Pozniak, C. J., Clarke, F. R., Clarke, J. M., Houshmand, S., & Singh, A. K. (2009). Chromosomal location of the cadmium uptake gene (Cdu1) in durum wheat. Genome, 52, 741–747. doi: 10.1139/G09-042

108. Dai, X., & Zhao, P. X. (2011). Psrnatarget: A plant small RNA target analysis server. Nucleic. Acids Res., 39, 155–159. doi: 10.1093/nar/gkr319

109. Mendoza-Soto, A. B., Sánchez, F., & Hernández, G. (2012). MicroRNAs as regulators in plant metal toxicity response. Frontiers in Plant Science, 3(105), 105. doi: 10.3389/fpls.2012.00105

110. Min Yang, Z. & Chen, J. (2013). A potential role of micrornas in plant response to metal toxicity. Metallomics, 5(9), 1184. doi: 10.1039/c3mt00022b

111. Zhou, Z. S., Song, J. B., & Yang, Z. M. (2012). Genome-wide identification of Brassica napus microRNAs and their targets in response to cadmium. Journal of Experimental Botany, 63(12), 4597–4613. doi: 10.1093/jxb/ers136

112. Wang, F., Wang, Z., & Zhu, C. (2012). Heteroexpression of the wheat phytochelatin synthase gene (TaPCS1) in rice enhances cadmium sensitivity. Acta Biochim. Biophys. Sin., 44, 886–893. doi: 10.1093/abbs/gms073

113. Wang, J., Mao, X., Wang, R., Li, A., Zhao, G., Zhao, J., & Jing, R. (2019). Identification of wheat stress-responding genes and *TaPR-1-1* function by screening a cDNA yeast library prepared following abiotic stress. Sci Rep., 9, 141. doi: 10.1038/s41598-018-37859-y

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ОСНОВИ СТВОРЕННЯ СОРТІВ ПШЕНИЦІ З НИЗЬКИМ РІВНЕМ НАКОПИЧЕННЯ КАДМІЮ

Серед важких металів кадмій (Cd) є вкрай токсичним для рослин і вважається одним із найбільш небезпечних елементів, що потрапляють у навколишнє середовище, навіть за низьких концентрацій. Розвиток промисловості й сільського господарства призвели до збільшення вмісту Cd у довкіллі та у ґрунтах сільськогосподарського призначення. Cd потрапляє у ґрунтове середовище при внесенні фосфорних добрив, гною, стічних вод тощо. Кадмій є другорядним елементом для росту рослин і відзначається високою токсичністю, що може серйозно впливати на ріст і розвиток рослин. Через високу мобільність кадмію в ґрунті, за концентрації цього металу вище критичного рівня може спостерігатися порушення росту й ушкодження клітин через аномалії біохімічних і фізіологічних процесів. Накопичення кадмію до фітотоксичного рівня призводить до зниження продуктивності рослин і втрат врожаю. Рослини, які ростуть в ґрунті, забрудненому кадмієм, є основним джерелом надходження Cd до організму людини.

Пшениця, рис і кукурудза є основними світовими продовольчими культурами. Серед них пшениця – основне джерело продуктів харчування для більш ніж половини населення світу. Порівняно з іншими важкими металами, кадмій легше засвоюється і накопичується пшеницею, що представляє неабияку загрозу для здоров'я людини. Саме продукти з пшениці є основним джерелом споживання Cd людиною. Рослини пшениці, в основному, накопичує Cd через кореневу систему, потім метал мігрує у надземну частину і, нарешті, накопичується у насінні рослини. Для зниження інтенсивності поглинання кадмію й токсичності рослин пшениці були спроби використовувати методи агрономічного менеджменту. Однак ці заходи можуть створювати деякі проблеми, а саме: великі капіталовкладення, високе споживання енергії, складність у застосуванні й вторинне забруднення.

Сорти пшениці зі здатністю до низької акумуляції кадмію є найбільш ефективним й економічно доцільним способом зниження ризику надходження цієї речовини в організм людини, пов'язаного зі споживанням харчових продуктів. В традиційній селекції відбір зразків пшениці, стійких до накопичення кадмію, здійснюється на основі морфологічних, фізіологічних або біохімічних показників, пов'язаних з Cd-стресом. Велике значення має вивчення молекулярного механізму абсорбції, й транспорту Cd у рослинах пшениці та створення сортів культури із низьким накопиченням цього металу для продовольчої безпеки людини.

Використання методів молекулярної селекції та їх успішна інтеграція з традиційними методами для створення сортів сільськогосподарських культур з низьким накопиченням Cd матиме важливе практичне значення для безпечного використання сільськогосподарських ґрунтів, забруднених Cd. Мета цього огляду – обговорити вплив кадмію на ріст і розвиток пшениці, механізми токсичності й толерантності до кадмію, а також деякі можливі стратегії селекції культури щодо підвищення толерантності та зниження акумуляції цього елементу. У статті розглядається вплив кадмію на ріст і розвиток рослин, особливості поглинання, перенесення й розподілу кадмію у пшениці, механізми толерантності та молекулярно-біологічні аспекти. Представлено стратегії та можливі схеми селекції створення сортів пшениці з низьким накопиченням кадмію.

***Ключові слова**: пшениця, кадмій; поглинання; транспорт; розподіл; механізм толерантності; молекулярні механізми.*

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