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WAYS OF THE CADMIUM ACCUMULATION MONITORING IN SUNFLOWER AND OTHER CROPS: OVERVIEW

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Steady trend of the last salt is an increase in the total concentration of dangerous elements and their compounds in agricultural soils. The consequence of this process is the growth of requirements for crop quality and the intensification of research aimed at forming a theoretical basis and finding practical ways to solve this problem.

With the development of industry, Cd pollution becomes more and more serious, which poses a serious threat to agricultural production and human health. Cadmium (Cd) is an important pollutant in farmland soil. Breeding of low Cd accumulation crops can reduce the risk of heavy metal removing into the human food chains and can solve the problem of food safety production in contaminated soil. Therefore, studies on Cd absorption and accumulation in crops have attracted the attention of researchers all over the world. The possibility of solving this problem (to create vatieties with low Cd accumulation) by selection methods in particular, sunflower, rice, wheat, soybean and maize, is considered in the article. From the other hand, the ability of individual crops and varieties to accumulate of high concentrations of harmful elements in the future can be realized as a separate selection and technological direction for the remediation of agricultural land.

This paper reviews and summarizes the physiological characteristics of uptake, transport and antioxidant response of crops to Cd stress. The differences between them indicate that different crop varieties adopt different adaptation strategies to Cd stress. The characteristics of Cd accumulation in several crops such as sunflower are expounded. Methods to reduce Cd uptake in crops and breeding strategies for low Cd are put forward. Finally, the problems and prospects of low Cd breeding are put forward. In order to further promote the breeding of Cd low accumulation crops, the breeding utilization should be strengthened in the future, too. It will provide important theoretical guidance and ideas for reducing Cd uptake in crops and low Cd breeding in the future.

The relevance of the problem of the cadmium controlling migration along the food chain determines the need of experimental studies, primarily in countries with the dominance of sunflower in the crops area structure.

Key words: *sunflower, breeding, Cd absorption, Cd transport, Cd distribution, Cd stress.*

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Introduction. Cadmium (Cd) is a ductile gray heavy metal, located in 12-th group of the fifth period of the periodic table, with atomic number 48 and molecular weight of 112,41 (Morrow, 2010). F. Stromeyer and K.S. Hermann discovered Cd in 1817 while purifying zinc oxide compounds. In the natural environment, Cd rarely exists in the form of elemental. It exits in the soil solution primarily as Cd^{2+} but also as Cd-chelates. The content of Cd in the earth's crust is very low. Throughout the world, the content of Cd in soil ranges from 0,01 to 2 mg kg^{-1}, with an average of 0,35 mg kg^{-1} (Yang et al., 2010). Due to its strong mobility and high phytoavailability in soil, Cd is readily taken up by plant roots (Chen et al., 2018; Huang et al., 2021; Sahito et al., 2022; Shahid et al., 2017; Yu et al., 2020).

Sunflower (*Helianthus annuus* L.) belongs to the family *Asteraceae* (Frey et al., 2020). The *Helianthus* genus contains 65 different species of which 14 are annual plants. The sunflower that the most people refer to is *H. annuus*, an annual sunflower. The plant has a rough, hairy stem, broad, coarsely toothed, rough leaves a circular heads of flowers. The heads consist of many individual flowers which mature into seeds on a receptacle base. Sunflower is the world's fourth largest oil-seed crop and its seed are used as food and its dried stalk as fuel. It is already been used as ornamental plant, too (Benavides et al., 2021; Zhao et al., 2011). Sunflower has a large biomass and shows high tolerance to heavy metals and therefore, are used in phytoremediation studies (Bayat et al., 2021; Benavides et al., 2021; Chae et al., 2014; De Andrade et al., 2018; Tang et al., 2003; Watai et al., 2004).

It is helpful for low Cd crop breeding to study the growth, physiological characteristics of Cd accumulation in plants. In the paper, referring to a large number of domestic and foreign literature the research results on the growth and physiological Cd accumulation in sunflower and other crops were summarized and analyzed, and two aspects of external environmental regulation and internal genetic improvement were proposed to reduce Cd accumulation. It is expected to provide reference for the prevention of soil Cd pollution and the breeding of low Cd grains to ensure the safety of food production and human health.

Cadmium pollution and toxicity. Cd content of 280 mg kg^{-1} was found in contaminated paddy soils in Thailand (Simmons et al., 2005). Cd levels in topsoil in some areas of northern

France are as high as 300 mg kg^{-1} (Sterckeman et al., 2000). The total land acreage where soil is above the safety threshold level was 16,1% in China, with Cd, nickel and arsenic being the top three inorganic pollutants, with frequencies of soils above the threshold concentrations being 7,0, 4,8 and 2,7%, respectively. Cd pollution is the most serious. Furthermore, Cd pollution in the soil plough layer in China is increasing at an average rate of 0,004 mg kg^{-1} per year, which is much higher than the rate in Europe (Luo et al., 2009).

Cd is a toxic heavy metal, excessive Cd in plants will affect the normal physiological functions of plants (Cornu et al., 2020; Dias et al., 2013; He et al., 2017; Jaouani et al., 2018; Lv et al., 2019; Rabêlo et al., 2021). Cd poisons plants in two ways:

1) large amount of free Cd^{2+} accumulates in plant cells, which interferes with the original ion balance and redox potential of the cells, resulting in the obstruction of ion absorption and transport in plant cells, the imbalance of cell osmotic pressure, and damaging normal metabolic process;

2) Cd combines with macromolecular substances such as nucleic acids, proteins, enzymes, etc., or replaces the central ions of these macromolecules, denaturates and inactivates them.

Its incorporation in plants has been reported to induce severe phyto-toxic effects such as it restricts the bio-synthesis of chlorophyll (Shahabivand et al., 2017), alters water status (Barcelo & Poschenrieder, 1990), reduces growth, particularly roots, interrupts mineral uptake and carbohydrate metabolism (Wang et al., 2008), encourages stomata closure (Zhu et al., 2020), retards the photosynthetic mechanism (Rabêlo et al., 2021), impairs the process of transpiration (Liñero et al., 2016), respiration and nitrogen assimilation (Wang et al., 2008) and consequently lowers biomass production (Ahmad et al., 2015; Fan et al., 2011; Jaouani et al., 2018; Qian et al., 2009; Wang et al., 2008; Zhou & Qiu, 2005).

Most of the Cd absorbed by the human body comes from the enrichment of the food chains, and selectively accumulates in the kidney (Yang et al., 2010) and liver (Qi et al., 2020). Kidney accumulates up to 1/3 of the total amount and is the target organ of Cd poisoning. Excessive Cd enrichment can cause renal function decline (such as renal tubular cell proliferation, necrosis or atrophy, etc.) and metabolism obstruction (such as glycosuria, proteinuria, amino acid urine) (Reyes-Hinojosa et al., 2019; Templeton & Liu, 2010). Among the Cd poisoning incidents, the most influential one was the "Itai-Itai disease" in the 1960's. Local residents had been eating water and rice polluted by Cd, Cd entered the human body and not be decomposable and accumulate for a long time, which leaded to joint pain, bone deformity and easily broken bones, and finally death (Aoshima, 2012). Since the toitaka disease incident in Fukuyama prefecture of Japan was identified as the result of soil Cd pollution in the 1960s (Qi et al., 2020), cases of human Cd poisoning caused by Cd pollution have been reported in other parts of the world (Bakulski et al., 2020; Genchi et al., 2020; Reyes-Hinojosa et al., 2019). Therefore, many countries in the world have formulated limit standards of heavy metals in some fertilizers. How to prevent or mitigate heavy metal soil pollution of cropland and ensure safe food production has become an important issue in modern world.

Physiological characteristics of Cd accumulation in crops. After Cd enters the root cells, part of the Cd is sequestered in vacuoles in the form of a Cd-plant chelate protein complex (Miyadate et al., 2011; Ueno et al., 2010), while the rest is transported to the xylem; separating Cd into vacuoles is considered to be an effective tolerance mechanism, which reduces Cd transport to the grains (Gao et al., 2016; Xin et al., 2018). Plants can also minimize the concentration of free Cd in the cytosol by forming metal chelates or complexes with phytochelatins or metallothioneins (Saraswat & Rai, 2011). J.J. Hart studied the biological processes in durum wheat of root Cd uptake, xylem Cd translocation to shoots and Cd accumulation in wheat grains; excessive Cd accumulation in durum wheat grains was not correlated with either seedling root influx rates or root-to-shoot translocation, but might be related to phloem-mediated transport of Cd to the grains (Hart et al., 1998)

Cadmium accumulation in rice grains was independent of root uptake time and Cd concentration in soil, but was strongly positively correlated with the Cd concentration in the xylem, with the Cd translocation *via* xylem from root to shoot being the major physiological process to determine the Cd concentration accumulated in rice grains (Shimpei et al., 2009).

T. Kensuke studied the contribution of rice phloem to the transfer of Cd to grains, and showed that 91–100% of Cd in grains was deposited in the phloem (Kensuke et al., 2007).

During reproductive growth, Cd is absorbed from the roots and transported to the grains via stems and leaves. It is deposited in the developing grains (Harris & Taylor, 2013), with the nodes being the central organ where xylem-to-phloem transfer takes place and which play a key role in the process by which Cd is transferred from the soil to the grains at the grain-filling stage.

Plants respond to Cd stress though adjusting their own physiological and biochemical processes, of which the accumulation and subsequent detoxification of reactive oxygen species (ROS) caused by heavy metals is one of the important aspects (Abbas et al., 2020; Chen et al., 2010a; Jan et al., 2021; Saidi et al., 2021; Wu et al., 2015a; Zhang et al., 2020). Cd stress disrupts the dynamic balance between production and quenching of ROS in plants (Lv et al., 2017). Excessive ROS accumulation changes enzyme activity (Hu et al., 2019), disrupts the metabolism of proteins, lipids and nucleic acids (Christophe et al., 2017), results in damage to membrane lipids by peroxidation (Dixit et al., 2001), and inhibits plant growth and development. In order to reduce the oxidative damage caused by the excessive ROS induced by Cd stress, plants have evolved antioxidant enzyme and non-enzyme systems during the long-term phylogenetic process (Liu et al., 2022). Antioxidant responses to Cd stress have been studied in many plant species, such as soybean (Li et al., 2012), wheat (Chen et al., 2017), barley (Chen et al., 2010b), rice (Singh et al., 2020), maize (Rehab & Ibrahim, 2020), rapeseed (Wu et al., 2015b) and millet (Han et al., 2018b).

Cadmium accumulation in crops. Sunflowers were subject to six levels of soil contamination (from 2,5 to 15 mg kg^{-1} Cd in soil) with no Cd control, from the emergence of the cotyledon leaves until the harvest, when sunflowers were at the flower bud stage. An overall increase of Cd concentration was found in all tissues of the plants (roots, stem, young, mature and old leaves) by increasing the Cd contamination in the soil. Regardless of treatments, Cd concentration in roots always exceeded those in the aboveground dry matter with a low translocation from roots to shoots (Alaboudi et al., 2018; Hawrylak-Nowak et al., 2015; Maria et al., 2013; Sadiq et al., 2019). Regarding Cd accumulation in sunflower seeds, the results indicated that Cd is translocated to seeds, and the cotyledons showed the highest concentration (Cd-high group), ranging from 10 to 20 µg g^{-1}. Considering both total concentration and the distribution in the seeds, Cd uptake is responsible to the homeostasis misbalance of micronutrients (Pessôa et al., 2017). When sunflower was grown hydroponically in greenhouse, being exposed to low concentrations of Cd, there were no significant effects on the partitioning of recent Cd, most of the recent Cd was recovered in roots (60 %) and only 2,8 % were found in seeds (0,8 % for the husk and 2,0 % for the almonds) (Liñero et al., 2016).

At present, various crops such as rice (Huang et al., 2021; Pan et al., 2020; Yan et al., 2021), maize (Dakak & Hassan, 2020; El-Hassanin et al., 2020; He et al., 2017), wheat (Ali et al., 2021; Khanboluki et al., 2018; Wang et al., 2020) and cotton (Zhu et al., 2020) have been studied for their Cd tolerance mechanism and low-Cd material screening.

Different crops or cultivars have different Cd accumulation ability in grains. A study showed that *indica* was easier to accumulate Cd than *japonica*, and the Cd content in grains of *indica* rice was 1,84–4,14 times higher than japonica (Kun et al., 2019). The Cd content of *indica* varieties may be higher than the national Cd limit under medium and low Cd contaminated soil conditions (Huiru et al., 2019).

Cd accumulation capacity is different in different organs of the same plant. According to the absorption and transport characteristics of Cd, most of the research results revealed that the order of Cd distribution in organs was basically root > stem > leaf > grain (He et al., 2017; Jun et al., 2020; Zhou & Qiu, 2005). Wen Zhiqi et al. (Wen Zhiqi et al., 2015) studied the characteristics of Cd accumulation in vegetative organs of 10 indica varieties, the results showed that the content of Cd in roots was the highest, was 4–13 times that of leaves, 8–10 times that of cob, and 20–40 times that of grains; During grain-filling, a large amount of Cd in leaves was exported to grains, so there was a high correlation between leaves and grains with a correlation coefficient of 0,769. For different rice varieties, the difference of Cd accumulation in grains mainly occurs in the reproductive stage (Kun et al., 2019), combining with the measures reducing Cd at the early stage of crop growth, carrying out appropriate agronomic measures which reduce the Cd availability in the soil and control the Cd uptake and transport to the grains can effectively reduce the Cd content in grains at the grain-filling stage. Yan et al. (2019) studied the allocation of Cd in wheat organs by isotopic tracer during flowering and grain maturation stage, and found that when the Cd concentration was high, the proportion of Cd transferred from root to stem and aboveground Cd distributed to grains was also high, and the Cd migrating at the flowering stage accounted for 40–45 % of Cd accumulation in grains on average.

Measures of reducing crop Cd accumulation. Appropriate use of traditional agricultural planting methods in Cd-contaminated farmland can not only make use of Cd-overaccumulated plants to remediate the soil, but also produce crops, which meet the national Cd limit standard (El-Hassanin et al., 2020; Kang et al., 2020; Li et al., 2017; Liu et al., 2016; Song et al., 2013; Yan et al., 2021). By properly managing soil moisture and nutrients, and by controlling soil pH and redox potential, farmers can reduce Cd migration from soil to root, helping to decrease Cd accumulation in grains (Hussain et al., 2021; Yuan et al., 2020). Water and fertilizer management has shown some positive effects in reducing the availability of heavy metals in soils (Belhaj et al., 2016; Grant et al., 2013; Murtaza et al., 2015; Zhu et al., 2020); flooding can reduce Cd accumulation in rice, while adding lime can have a similar effect (Han et al., 2018a), although it has been reported that flooding may increase the accumulation of as in crops (Hu et al., 2013; Wang et al., 2015). Showed that film mulch technology could reduce Cd content in rice by 50 % compared with the control; when combined with other measures (biochar + silica foliar fertilizer), Cd content in grains could be reduced even further. At present, the effects of factors, applied singly or in combination, on the control of Cd pollution are being studied (Monu et al., 2008; Tang et al., 2020; Zhou et al., 2020), but such studies have not been sufficiently systematic. Due to the complexity and diversity of crop Cd pollution sources, further research still needs to be carried out.

Low Cd breeding. Sunflower is an important cash crop in Ukraine, however, for conditions of Ukraine with average dose of phosphorus fertilizers 60 kg in the soil is introduced annually 30–35 g $hectare^{-1}$ of Cd. This is the factor that determines a rather high average concentration of Cd in the arable lands of Ukraine, about 0,15 mg kg^{-1} of soil. But according to EU standards, sunflower Cd accumulation should not be more than 0,05 mg kg^{-1}, therefore, the study on resistance to Cd and low Cd materials selection for sunflower is very important.

Cd accumulation in cereal grains is a serious threat to food safety and human health. Cultivating low-Cd crop varieties is one of the most effective ways to reduce Cd toxicity (Grant et al., 2008a, 2008b; Ishikawa, 2020; Liu et al., 2020; Sun et al., 2015; ZaidImdad et al., 2018). But there are few reports on the breeding of varieties with low Cd in sunflower. Li Yinming et al. (Li et al., 1995) screened 200 germplasm sunflower resources, and selected two varieties with low Cd accumulation, Primrose and HA290, and two maintain lines, HA323 and RHA324 with medium content of Cd. Two new low Cd varieties HA448 and HA449 were selected by screening the later generation of HA323/HA290. RHA324/Primrose was selected as RHA450 recovery line. The average Cd content of HA448/RHA450 and HA449/RHA450 hybrids was reduced by more than 50 % in the three-year experiment from 2000 to 2002 (Miller JF et al., 2005). Then, he investigated variability of grain Cd levels on sunflower by field experiment, and to seek an efficient screening method for future breeding. The result showed the kite there were large variations in leaf Cd concentration among 200 sunflower lines. The positive correlation between R5 leaf Cd and kernel Cd level was obtained from nonoil-seed hybrid. Indicates that an efficient and low-cost screening method can be developed for genotype selection, but plants must be grown to the R5 stage.

Breeding low Cd accumulation sunflower cultivars is the fundamental method to solve the problem of low Cd intake the breeding process is long and complicated. The breeding process probably includes:

– Finding materials with low Cd genes;

– Finding materials with high yield, stable yield, resistance to disease and insect pests, wide adaptability and other high quality materials except low Cd characteristics, this materials should be the main cultivars, taking into account other excellent characteristics such as herbicide tolerance, drought and flood resistance, maturity period and so on;

– to understand the genetic characteristics of Cd gene, and to formulate the low Cd hybridization breeding strategy assisted by modern biotechnology;

– evaluate and select hybrid offspring materials, and select new cultivars (lines) with low Cd, high quality and good comprehensive characteristics;

– experimental adaptive planting of new cultivars (lines), observation and evaluation of traits stability.

Except the above problems, there are the following situations. Are the excellent characteristics of the new breeding materials, such as low grain Cd concentration, stable and acceptable in the move from the laboratory to the test plot and then to the field? Is there an optimal planting region for the low Cd cultivars identified by trialing throughout the growing regions? As a consequence, gene manipulation techniques (e.g., transformation or gene editing) and their application to new cultivar development should be treated with caution and evaluated comprehensively and systematically. Whether such new low Cd cultivars can be successfully developed by breeders, and would have the characteristics allowing them to be widely adopted by farmers, has yet to be confirmed.

Conclusions. Cd pollution affects the growth and reduces the yield and quality of crops, and poses a threat to human health, which have aroused widespread concerns all over the world. In order to reduce the Cd concentration in cereal grains and to ensure safe food production and avoid human health risks, scientists have carried out extensive and in-depth research into the problem of Cd contamination of food crops. Researchers have studied the uptake, transport and accumulation of Cd in crops, analyzed the physiological and metabolic mechanisms operating under Cd stress, and proposed a number of measures to control and prevent Cd accumulation in crops. At present, although the Cd concentrations in the grains of most crops produced in most parts of the world are within the safe tolerable range for human consumption, Cd pollution will become increasingly serious if steps to control Cd pollution are not strictly enacted. Therefore, the need to reduce Cd pollution is urgent, and the basic researches, and its practical applications, related to reducing Cd accumulation in the edible parts of crops, need to be undertaken urgently.

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Шляхи контролю накопичення кадмію в соняшнику й інших культурах: огляд

Стійким трендом останнього століття є збільшення загальної концентрації небезпечних для здоров'я елементів та їх сполук у землях сільськогосподарського використання. Наслідок цього процесу – зростання вимог до якості врожаю й активізація досліджень, спрямованих на формування теоретичного базису та пошук практичних шляхів вирішення цієї проблеми.

Розвиток промисловості та збільшення виробництва синтетичних добрив зумовлюють зростання ризиків, пов'язаних з отриманням неякісних продуктів харчування, їхнього впливу на здоров'я людей. Кадмій є одним з основних елементів, що викликають забруднення сільськогосподарських угідь. Одним із шляхів зменшення негативного впливу цього важкого металу у трофічних ланцюгах є створення сортів із низьким рівнем накопичення кадмію. Широкий спектр досліджень, пов'язаних із контролем розповсюдження металу, пояснюється стійкою тенденцією до розширення площі забруднених земель та зростання середнього показника вмісту кадмію в орних ґрунтах. Можливість селекційного вирішення цієї проблеми нині розглядається для таких культур, як соняшник, рис, пшениця, соя, низки інших. На противагу цьому, здатність окремих культур і сортів до накопичення високих концентрацій шкідливих елементів у перспективі може бути реалізована як окремий селекційний та технологічний напрям для ремедіації орних земель.

У статті розглянуті особливості поглинання, транспортування й інших фізіологічних процесів, пов'язаних із накопиченням кадмію в сільськогосподарській продукції. Проаналізовано відмінності у стратегії адаптації рослин до кадмієвого стресу. На прикладі соняшнику наведено характеристики шляхів надходження та накопичення кадмію в окремих органах рослин. З метою подальшого сприяння вирощуванню культур із низькою здатністю до поглинання металу в майбутньому варто посилити використання можливостей селекційного процесу. Важливо розробити теоретичну основу й окреслити практичні шляхи щодо зменшення поглинання кадмію сільськогосподарськими культурами, успішної селекції на здатність до низької акумуляції цього металу. Запропоновано методи зниження поглинання цього елемента культурами, проаналізовано стратегії селекції на здатність рослин до низької акумуляції кадмію. Висвітлено селекційні перспективи створення сортів із низьким рівнем накопичення кадмію.

Актуальність проблеми контролю міграції кадмію за харчовим ланцюгом зумовлює необхідність проведення експериментальних досліджень, насамперед у країнах з домінуванням культури соняшнику у структурі посівних площ.

***Ключові слова:** соняшник, селекція, поглинання кадмію, транспорт кадмію, розподіл кадмію, кадмієвий стрес.*

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