Effects of Cadmium Stress on Rapeseed Growth and Nutrient Accumulation

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Abstract

Currently, heavy metal - contaminated farmland has emerged as a critical issue in agricultural production. Employing plants' ability to hyper - accumulate and adsorb heavy metal elements represents a green, cost - effective, and efficient approach to remediate polluted soil. Rapeseed exhibits a remarkable capacity to absorb and accumulate cadmium. This study comprehensively reviews the recent research progress regarding the impacts of cadmium stress on rapeseed growth and nutrient accumulation. The review encompasses aspects such as the absorption, transportation, accumulation, and distribution of cadmium within rapeseed, the influence of cadmium stress on rapeseed growth and development, and the application prospects of rapeseed in cadmium pollution remediation. The objective is to offer a scientific foundation for the feasibility of utilizing rapeseed cultivation to remediate heavy - metal - contaminated soil.

Keywords

Organic contamination; Cadmium; Rapeseed growth; Nutrient accumulation.

1. Introduction

In recent years, the extensive use of fertilizers and pesticides in agriculture, sewage irrigation, and industrial metal smelting activities have led to a more severe problem of heavy metal pollution in soil (Sundaramoorthy P et al., 2015). According to the "National Soil Pollution Survey Bulletin" released in China in 2014, the exceedance rate of cadmium (Cd) pollutant sites in cultivated land reached 7.0%, and the area of Cd - contaminated land exceeded 280,000 hm^2 (Li Yujun et al., 2017). Thus, it is of great urgency to effectively control and remediate soil Cd pollution. Once the soil is contaminated by heavy metals, heavy metals may accumulate in large quantities in plant bodies and seeds. This not only seriously impedes the growth and development of plants but also affects the yield and quality of crops (Xiao Ting et al., 2006). Cadmium (Cd) pollution is one of the common types of heavy - metal pollution. Besides the general characteristics of heavy - metal pollution like concealment, irreversibility, and long - term persistence, due to its high mobility in soil, strong toxicity to crops, and resistance to degradation, it is considered a highly hazardous pollutant element among heavy metals. Cadmium can damage the photosynthetic organs and chloroplast structure of plants, inhibit the growth of plant roots, and increase the permeability of the plasma membrane. Consequently, it disrupts the absorption and accumulation of nutrient elements by plants, and this toxic effect intensifies with the increase in cadmium concentration (Francesca D V et al., 2005; Belimov A A et al., 2003; Zhang G P, 2002). The significant accumulation of cadmium in crops, especially in edible parts, can pose a threat to human health through the food chain (Grant C A et al., 1998).

Phytoextraction is a method of remediating polluted soil by leveraging plants' ability to hyper - accumulate heavy - metal elements. It has attracted widespread attention from various sectors of society due to its advantages of not disrupting the soil ecological environment, causing no secondary pollution, and being easy to implement (SAIER M HJR and TREVORS J T, 2010; MUTHUSARAVANAN S et al., 2018). Through long - term screening research, it has been discovered that plants of the Brassicaceae family have a strong ability to absorb and accumulate Cd. Brassica napus L., belonging to the Brassicaceae family, is one of the major crops in China. It has a long - standing cultivation history and rich planting experience, and plays a crucial role in social and economic development. Rapeseed is widely planted in both northern and southern regions of China, with an annual planting area of approximately 7 million hm^2 (Wang Hanzhong, 2018). Rapeseed has a large biomass during growth, and its planting technology is mature and easy to master. Research indicates that Brassica napus L. has the ability to remediate soil contaminated with Cd, Cu, etc., and is a Cd - hyperaccumulating plant. Moreover, since Cd ions are insoluble in oil, they do not affect human diet. Therefore, rapeseed can be used as an alternative crop for remediating soil contaminated with Cd and other heavy metals, especially in typical large - scale Cd - contaminated areas, representing a green, economic, and efficient soil remediation technology.

2. Absorption, Transportation, Accumulation, and Distribution of Cd in Rapeseed

2.1. Absorption and Transportation of Cd in Rapeseed

The absorption of Cd by plants is influenced by multiple factors, including the Cd content in the soil, soil texture, organic matter, pH value, temperature, and rhizosphere microorganisms. Among these, the Cd concentration in the soil is the decisive factor for the amount of Cd absorbed by plants. As the soil Cd concentration increases, the Cd content in plants rises significantly (Chen Fei, 2009). More than 50% of the Cd accumulated in plants is absorbed through the roots (Salah S A and Barrington S F, 2006). In plant root cells, Cd mainly accumulates in the apoplast, particularly in the cell wall, in the form of Cd^{2+} or Cd - chelate (Jiang Hanming et al., 2012). Cd ions enter plant roots via two main pathways: the apoplast pathway and the symplast pathway. The former is a passive transport process that does not require energy consumption and is mainly driven by the concentration gradient between the medium and the plant body. The latter is an active transport process that requires energy (Meng Guiyuan et al., 2012). The absorption of Cd by rapeseed roots from the soil solution mainly depends on the content of exchangeable Cd in the soil solution, which is closely related to the soil pH value (Yang Zhongfang et al., 2015). Additionally, Cd can enter plant cells through the transport systems of other trace elements, such as via the transmembrane carriers of Ca^{2+}, Fe^{2+}, Cu^{2+}, and Zn^{2+}. Due to the similar chemical properties of Zn, Fe, and Cd, there is an antagonistic effect among them during root absorption.

After the roots absorb Cd from the soil solution, the Cd in the roots undergoes fixation and compartmentalization in root cells, is transported to the stele through the symplast, and then is released into the xylem. After being loaded into the xylem, it is transported to the above - ground parts under the influence of transpiration (Pineros M A et al., 1998), and then further transported to the plant seeds through the phloem (Hart J J et al., 1998). The process of Cd^{2+} being transported from the underground parts (roots) to the above - ground parts of the plant can be divided into two stages: one is entering the xylem vessels, and the other is transportation in the vessels. In plant roots, Cd mainly exists in the form of sodium chloride - extractable state, which makes it easier for Cd in the underground parts to be transported to the above - ground parts (Xu Jialin et al., 1991).

2.2. Accumulation and Distribution of Cd in Rapeseed

The accumulation of Cd^{2+} in plants varies among different species, varieties, and even different organs of the same plant (Florijn P J and Van Beusichem M L, 1993). Xiang Dan et al. (2009) studied the differences in cadmium accumulation in various organs of the high - cadmium - absorbing rapeseed variety Zhucanghuazi and the low - cadmium - absorbing rapeseed variety Chuanyou Ⅱ - 93. They found that the difference in cadmium - accumulating ability between the two varieties was mainly reflected in leaves and stems. As the soil cadmium content increased, the proportion of cadmium absorbed by the above - ground parts of the high - cadmium - absorbing rapeseed Zhucanghuazi transferred to leaves gradually increased, while that of the low - cadmium - absorbing rapeseed Chuanyou Ⅱ - 93 transferred to stems gradually increased. Generally, the absorption of Cd^{2+} by most plants increases with the increase in the Cd^{2+} concentration in the soil (Jia Xia et al., 2011). The heavy metals accumulated by plants mainly have two destinations: one is the apoplast and vacuole (at the cell level), and the other is the sub - epidermal cells, upper - epidermal cells, and trichomes (at the tissue level). Some studies have shown that the roots and stems of rapeseed are the main organs for storing Cd (Xie Yunhe et al., 2014). Currently, it is generally believed that the Cd content in the above - ground parts of rapeseed is higher than that in the underground parts (Lü Jianbo et al., 2005; Wang Jiqing et al., 2003; Su Dechun et al., 2002; Shen Zhenguo et al., 1998; Kong Wenjie et al., 2006). However, some studies have also found that the accumulation of Cd in the roots of rapeseed is greater than that in the stems and leaves (Ma Jianjun et al., 2004). The transportation of Cd from the roots to the above - ground parts through the xylem is affected by root pressure and transpiration. The stronger the transpiration, the easier it is for Cd to migrate to the above - ground parts, and the higher the Cd content in the above - ground parts of rapeseed (Gao Qianlei, 2007). The transfer rate of Cd from rapeseeds to rapeseed oil is negatively correlated with the protein content in rapeseeds. The cadmium content in rapeseed meal is twice that in rapeseed oil, and the transfer rate of Cd from rapeseeds to rapeseed oil is 2% - 10%.

3. Effects of Cadmium Stress on Rapeseed Growth and Development

The impact of Cd on plant growth shows a "low - concentration promotion and high - concentration inhibition" phenomenon (Yang Hongxia et al., 2019). Zhang Lina et al. (2007) found that low - concentration Cd could promote the growth of rice seedlings when studying the effect of Si on rice seedlings under low - Cd - polluted conditions. Under Cd stress, there are certain differences in the germination process of rapeseed seeds. Generally, low - concentration Cd has no effect on or promotes the germination rate, germination potential, and vigor index of seeds, while high - concentration Cd inhibits the germination rate and vigor index of seeds. Heavy - metal stress can cause changes in the plant height and chlorophyll content of rapeseed. When the soil Cd concentration is relatively low (< 5 mg/kg), it can promote the growth and development of rapeseed to a certain extent, mainly manifested as promoting rapeseed growth, increasing plant height and biomass. However, when the concentration increases (≥ 5 mg/kg), the promoting effect turns into an inhibitory one. Cd^{2+} can interfere with the chlorophyll synthesis process in plants (Fridovich I, 1978), inhibit the biosynthesis of chlorophyll (Stobart A K et al., 1990), reduce the chlorophyll content, and thus inhibit plant photosynthesis. This is mainly manifested as hindering rapeseed growth, suppressing plant height, causing leaf chlorosis, and reducing biomass (Xu Suqin et al., 2005; Jiang Haidong et al., 2006). Moreover, the higher the concentration, the more obvious the inhibitory effect. The plant cell membrane system can not only maintain the stability of the internal environment of cells but also plays a crucial role in material transport, energy conversion, and information transfer. It can also make the biochemical reactions in cells proceed without interference. Under Cd^{2+} stress, reactive oxygen species and other free radicals are generated in plants, leading to oxidative stress and causing changes in membrane permeability (Yang Weidong et al., 2008).

4. Effects of Cadmium Stress on Nutrient Element Accumulation in Rapeseed

Cd may affect the absorption and accumulation of some nutrient elements by changing the permeability of the cytoplasmic membrane, thereby causing changes in the nutrient elements and components in plants and seeds (Gussarson M et al., 1996; Zhang G P et al., 2002). Excessive cadmium absorption can disrupt the nutrient balance and inhibit the absorption and transportation of nutrient elements. This is mainly because Cd^{2+} damages the roots and causes absorption antagonism, affecting mineral metabolism and the nutritional status of plants, and thus being toxic to plants (Zhong Weigong et al., 2006; Wang Songliang et al., 2007; Peng Shaolin et al., 2004). The research results of Cao Chunxin et al. (2011) show that excessive cadmium reduces the transport rate of N, P, and K to rapeseed leaves, resulting in a significant decrease in the N, P, and K content in plants. At the same time, the N, P, and K content in the soil increases significantly with the increase in the added cadmium concentration. This may be due to the inhibition of the absorption and transportation of N, P, and K in the soil by plants under cadmium stress. Many studies have shown that Cd stress can significantly affect the absorption and in - plant transportation of essential elements (such as Fe, Mn, Zn, and Cu). Most studies have found that Cd stress reduces the concentration and content of these essential elements in plants (Zhang S J et al., 2002). Wu Feibo (2002) found in the study on the effects of different cadmium levels on barley nutrient absorption that Cd toxicity significantly reduces the absorption and accumulation of Zn and Mn and significantly increases the accumulation of Fe in roots, leading to an imbalance of nutrient elements in barley seedlings and inhibiting their growth. Zhang et al. (2009) also found that Cd stress significantly changes the contents of trace elements such as Fe, Mn, Zn, and Cu in tomato seedlings. Cd stress not only reduces the photosynthetic rate of mung bean seedlings but also decreases the contents of Fe, Mn, Zn, and Cu in the stems and leaves of seedlings and promotes the accumulation of Zn, Fe, and Cu in roots. This indicates that Cd can affect the growth, development, and photosynthesis of plants by changing the accumulation of trace elements in plants (Zhang Yuanhua, 2016). The experiments of Zhang Shujie et al. (2011) also obtained similar results. The addition of Cd significantly affects the concentrations and contents of trace elements Fe, Mn, Zn, and Cu in the seedlings of Zhongshuang 9 rapeseed. Therefore, many researchers believe that causing disorders in the metabolism of trace elements in plants is another main reason for the inhibition of plant growth by Cd (Zhang S J et al., 2002; Toshihiro Y et al., 2006; Wang M et al., 2007).

5. Summary and Prospect

Cadmium is a highly concerned heavy metal in soil pollution remediation. It has a wide range of pollution sources and is likely to accumulate in soil. In the biosphere, cadmium can cause harm to organisms through migration, transformation, enrichment, and the "biomagnification" effect of the food chain. Rapeseed belongs to the Brassicaceae family. In recent years, studies have found that many plants of the Brassicaceae family have a strong ability to absorb certain heavy metals. Therefore, rapeseed can be used as a plant resource for remediating heavy - metal - contaminated soil. There are significant differences in the cadmium - absorbing and - accumulating abilities of different rapeseed varieties in China's rapeseed germplasm resources.

Some varieties have the potential to remediate cadmium - contaminated soil. At the same time, as an important oil - bearing crop, rapeseed has great economic value and occupies an important position in the agricultural field. Currently, research on the effects of Cd on rapeseed mainly focuses on the physiological changes of rapeseed seeds and the above - ground parts of seedlings, the accumulation and distribution laws of Cd in various organs of rapeseed, and the tolerance of rapeseed to Cd. However, the vast majority of these studies are short - term studies using hydroponics and pot experiments, which limits the effectiveness of applying the research results to field applications. In addition, most studies mainly focus on the accumulation of Cd in various organs of rapeseed plants, and there is relatively little research on the fate of Cd after the seeds are processed into rapeseed oil and meal. Existing studies (Yang Y et al., 2016) show that after seed processing, Cd mainly exists in the meal, and the Cd content in the oil is relatively low. However, this still needs to be further verified by subsequent research.

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