Comprehensive Evaluation of the Efficient and Safe Utilization of Two Varieties of Winter Rapeseed Grown on Cadmium- and Lead-Contaminated Farmland under Atmospheric Deposition

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Abstract: To determine the feasibility of planting rapeseed to safely utilize heavy metals (HMs)-contaminated farmlands surrounding working smelters under atmospheric deposition, a field trial was conducted to analyze the yields, cadmium (Cd) and lead (Pb) concentrations, health risks, and economic benefits of 15 rapeseed cultivars (13 *Brassica napus* L. and two *Brassica campestris* L.) in Jiyuan City, Henan Province, China. The results show that the seeds’ Cd concentration was 0.12–0.64 mg·kg\(^{-1}\) and the seeds’ Pb concentration was higher than Cd at 0.49–1.22 mg·kg\(^{-1}\). The Cd bioconcentration factor of *B. campestris* (0.702–0.822) was higher than that of *B. napus* (0.246–0.502). Additionally, Cd and Pb transfer factors from the stems to the pods and seeds were 0.34–1.20 and 0.54–4.53, respectively. Combined with a comprehensive analysis of the annual deposition data of Cd and Pb, 16.40 and 345.79 kg·hm\(^{-2}\), respectively, HMs in the seeds were not only derived from those in the soil, but were also derived from the atmosphere. Furthermore, the Cd and Pb levels in rapeseed oil, meal, and straw met the requirements stipulated in the standards for food safety, feeds hygiene, and organic fertilizer in China. Rapeseed–maize rotation yielded a profit of 15,550 CNY·a\(^{-1}\)·hm\(^{-2}\), thereby increasing the economic output by 133.8%. A cluster analysis revealed that *B. campestris* SYH and ZS100 and *B. napus* ZY-821 showed the greatest comprehensive benefits. In conclusion, rapeseed cultivation is a viable and extendable approach that can achieve the safe utilization of typical HMs-contaminated farmland caused by atmospheric deposition in Northern China.

Keywords: heavy metal; soil pollution; smelter; *Brassica* sp.; health risk

1. Introduction

Contamination by heavy metals (HMs) is an environmental issue of universal concern [1]. The National Soil Pollution Survey Bulletin of China from 2014 stated that Cd and Pb site-exceeding percentages were 7.0 and 1.5%, respectively. Farmland soil in 25 regions of 11 provinces in China are contaminated with Cd, covering a total area of more than 13,000 hm\(^2\) [2]. HMs are invisible and characterized by poor mobility, long residence times, and irreversibility in soil [3], leading to a reduction in soil quality and threatening crop growth and the safety of agricultural products [4]. Additionally, HMs endanger human health via bioamplification and bioaccumulation in the complex food chains and webs, presenting possible hazards for the ecological environment’s long-term development [5].
Although there are several exogenous input factors for HMs contamination in agricultural production, the two primary ways through which plants accumulate HMs are absorption from the soil or from atmospheric dust [6]. Some studies have revealed that atmospheric Pb is the primary contaminant in the aboveground parts of leafy vegetables [7]. HMs in atmospheric particles can not only be absorbed by plants through the stomata and epidermal cells, but can also indirectly enter plants through the roots after their deposition in the soil [8]. According to earlier statistics, the atmospheric Cd deposition in North China’s farmland from 2016 to 2020 reached 0.03 mg·m\(^{-2}\)·a\(^{-1}\) on average [9]. The statistical report on Jiyuan National Economic and Social Development states that in 2021, the Pb output of Jiyuan City, which was one of the nation’s principal Zn and Pb smelting facilities, reached 118 × 10\(^4\) tons. The annual increases in Cd and Pb concentrations were 0.16 and 4.16 mg·kg\(^{-1}\), respectively, in 0–20 cm of surface soil owing to atmospheric deposition from the surrounding working smelters [10]. In addition, Cd- and Pb-contaminated farmlands cover 384 km\(^2\) [10], and various degrees of HMs contamination have been observed in wheat seeds [11].

The annual planting area of rapeseed in China is approximately 6.5 million hectares, which accounts for approximately 20% of the global rapeseed planting area [12]. Several Brassica crops, including Brassica campestris L., Brassica juncea L., and Brassica napus L., have been proven to possess HMs-accumulating capacity [13]. The movement of HMs through the xylem from the underground parts to the shoots, the xylem to the phloem, and directly through the phloem affect the distribution of HMs within different rapeseed tissues, whereby only trace HMs are transported to the pods and seeds [14]. Furthermore, rapeseed can retain a higher biomass, which makes it an excellent candidate for soils contaminated by HMs [15,16]. Rapeseed plantations also provide economic benefits. Rapeseed is the greatest domestic source of vegetable oil in China [17], and rapeseed straw and oil residue can serve as animal husbandry feed or as organic fertilizers. However, the ability of different cultivars to absorb, accumulate, and tolerate HMs varies considerably. Additional research is required to explain the differences in the adaptation and tolerance of rapeseed cultivars, and to establish a planting mode for the safe production and utilization of HMs-contaminated soils.

In this study, large-scale planting trials were conducted on farmland in typical HMs deposition areas around smelting enterprises in northern China. Fifteen winter rapeseed cultivars belonging to B. napus and B. campestris were used as the experimental plants. We investigated the biomass of 15 rapeseed cultivars, as well as their Cd and Pb accumulation and translocation capacities. Furthermore, we evaluated the seed oil quality, the human health risks from the seed oil, the safety of meal and straw utilization, and assessed the cost–income and comprehensive benefit. Finally, we determined the adaptability and feasibility of winter rapeseed planting in farmland soils with moderate to mild atmospheric deposition-caused Cd and Pb pollution.

2. Materials and Methods

2.1. Experimental Site

This research was carried out at the Tangshi HMs-contaminated Farmland Remediation Base in Jiyuan City, Henan Province, China (Figure S1). The area’s latitude and longitude are 112° 31′ 30″ N, 35° 8′ 34″ E, respectively, with a temperature, precipitation, and sunshine duration of 14.6 °C·a\(^{-1}\), 860 mm·a\(^{-1}\), and 1727.6 h·a\(^{-1}\), respectively. The presence of Pb–Zn smelters around the test area still causes some HMs input to farmland by atmospheric deposition. The monthly monitoring results for HMs deposition through atmospheric dust falling in the Tangshi experimental area are shown in Figure S2; the annual Cd and Pb deposition values were 16.40 and 345.79 kg·hm\(^{-2}\), respectively. Table S1 lists the soil’s physicochemical characteristics and its quantitative properties. The concentrations of Cd and Pb were both higher than the risk screening values of 0.6 and 170 mg·kg\(^{-1}\),
respectively, stipulated in the Soil Environmental Quality–Risk Control Standard for soil contamination of agricultural land (GB15618-2018) (pH > 7.5) [18].

2.2. Experimental Design

Two types of B. campestris (Zaoshu 100 and Sanyuehuang) and thirteen types of B. napus (Shuangyou-8, Shuangyou-10, Shuangyou-092, Shuangyou-123, Shuangyou-195, Qinyou-1, Qinyou-10, Zashuang-6, Zashuang-7, Fengyou-10, Zhongyou-821, Jinyou-4, and Yuyou-2) were selected as the target plants based on the research on the early stages of winter rapeseed cultivars conducted by our team. The rapeseed seeds were purchased from the Henan Academy of Agricultural Sciences, and the cultivar information was also provided by them. The basic information for each cultivar is presented in Table 1. A randomized plot design was used in the experiments. Each plot had an area of 10 m² and the plot experiments were conducted in triplicate for each winter rapeseed cultivar. The planting density of winter rapeseed was set at 10 × 30 cm (plant spacing × row spacing) to increase the planting density and improve the yield without affecting the normal rapeseed growth. In October 2020, the seeds were selected and sown in each plot. During the rapeseed growing period, fertilizer and watering were applied in accordance with local farmer practices. In May 2021, when the rapeseed had reached maturity, we conducted sampling, yield evaluation, and seed harvesting.

Table 1. Basic information for the tested winter rapeseed cultivars.

<table>
<thead>
<tr>
<th>Type</th>
<th>Cultivar</th>
<th>Seed Color</th>
<th>Place of Origin</th>
<th>Yield (kg·hm⁻²)</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
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<td>2700</td>
<td>SY-8</td>
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<td></td>
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<td>SY-10</td>
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<td>Henan Province, China</td>
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<td>SY-092</td>
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<td>SY-123</td>
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<td>Black</td>
<td>Henan Province, China</td>
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<td>QY-1</td>
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<tr>
<td></td>
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<td>QY-10</td>
</tr>
<tr>
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<td>JY-4</td>
</tr>
<tr>
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<td>YY-2</td>
</tr>
<tr>
<td>Brassica campestris</td>
<td>Zaoshu 100</td>
<td>Black</td>
<td>Shaanxi Province, China</td>
<td>3000</td>
<td>ZS100</td>
</tr>
<tr>
<td></td>
<td>Sanyuehuang</td>
<td>Yellow</td>
<td>Henan Province, China</td>
<td>3300</td>
<td>SYH</td>
</tr>
</tbody>
</table>

2.3. Sample Analysis

When the rapeseed reached the mature stage, plant and soil samples were collected from each cultivar. Most of the leaves of the rapeseed fell off during maturity under field conditions and, in our previous research, we found that the concentrations of Cd and Pb in the stems and leaves of rapeseed were similar [19,20]. Therefore, the remaining leaves were added to the stem for detection and analysis in this study. A five-point sampling method was used to gather the roots, stems, pods, and seeds of the 15 rapeseed cultivars. These samples were washed thoroughly, oven-dried for 30 min at 105 °C, and then oven-dried to a constant weight at 65 °C. Rapeseed oils were processed using two oil-producing techniques: mechanical pressing (MP) and subcritical low-temperature butane extraction (SBE). Using concentrated HNO₃ and HClO₄ (5:1, v/v), the levels of Cd and Pb in the rapeseed tissues, rapeseed oil, and byproduct meal were determined using the wet method. The soil samples were air-dried and sieved. The concentrations of soil HMs were quantified using the USEPA method 3050 B after digestion with HNO₃-H₂O₂ [21]. Cd and Pb
were measured using an inductively coupled plasma mass spectrometer (ICP-MS, Elan DRC-e, Perkin Elmer, Waltham, Massachusetts, USA). During the determination process, blank standards, 2% parallel samples, a national standard soil sample GBW07402 (GSS-2) [22], and a national standard plant sample GBW07603 (GSV-1) were set for chemical analysis quality control (95 ± 5%) [23].

2.4. Computational Formula

2.4.1. Transfer Factor

The transport of HMs between the various rapeseed tissues was assessed using the transfer factor (TF). The formula is defined as follows:

\[ TF_1 = \frac{C_{stem}}{C_{root}} \]  
\[ TF_2 = \frac{(C_{pod+seed})}{C_{stem}} \]

where \( C_{root} \) (mg·kg\(^{-1}\)), \( C_{stem} \) (mg·kg\(^{-1}\)), and \( C_{pod+seed} \) (mg·kg\(^{-1}\)) represent the HMs concentrations in the root, stem, and pod and seed of the rapeseed, respectively.

2.4.2. Bioconcentration Factor

The HMs accumulation capacity of the rapeseed was assessed using the bioconcentration factor (BCF). The formula is defined as follows:

\[ BCF_i = \frac{C_{plant}}{C_{soil}} \]

where \( C_{plant} \) (mg·kg\(^{-1}\)) represents the HMs concentrations in the rapeseed tissues and \( C_{soil} \) (mg·kg\(^{-1}\)) represents the HMs concentrations in the soil.

2.4.3. Health Risk Assessment

A chemical carcinogenic/non-carcinogenic risk assessment model was used to assess the health risks posed by HMs during rapeseed oil intake. Cd is a chemical carcinogen, and the risk assessment model for chemical carcinogens was estimated as follows:

\[ CR_i = ADD_i \times SF_i \]

where \( CR_i \) represents the probability of a person developing cancer if exposed to a particular carcinogenic metal over the course of their lifetime, and \( SF_i \) is the corresponding slope factor (15 mg·kg\(^{-1}\)·d\(^{-1}\) for Cd) [8]. For regulatory purposes, the acceptable or tolerable risk ranges from \( 1 \times 10^{-6} \) to \( 1 \times 10^{-4} \) [24].

Pb is a non-carcinogenic chemical, and the chemical non-carcinogenic risk assessment model is defined as follows [25]:

\[ HQ_i = \frac{ADD_i}{RfD_i} \]

where \( HQ_i \) represents the potential health risk to a human exposed to a specific non-carcinogenic metal based on the hazard quotient, and \( RfD_i \) represents the reference daily dose through ingestion (3.5 \( \times 10^{-3} \) mg·kg\(^{-1}\)·d\(^{-1}\) for Pb) [26]. When \( HQ_i < 1 \), the health risks are less likely; however, when \( HQ_i > 1 \), the health risks may become apparent.

The following formula was used to calculate the daily oral intakes of Cd and Pb:

\[ ADD = \frac{(EF \times ED \times C_m \times IR)}{(BW \times AT)} \]

where \( ADD \) represents the average daily dose (mg·kg\(^{-1}\)·d\(^{-1}\)), \( EF \) represents the exposure frequency (d·a\(^{-1}\)), \( ED \) represents the exposure years (a), \( C_m \) represents the HMs concentrations of rapeseed oil (mg·kg\(^{-1}\)), \( IR \) represents the ingestion rate, \( BW \) represents the average body weight (16 kg for children and 65 kg for adults), and \( AT \) is the mean exposure time (\( ED \times 365 \)). The \( IR \) data for rapeseed oil were obtained from the China Statistical Yearbook’s main food consumption data for Henan Province in 2020.
2.4.4. Economic Cost Assessment

The economic cost assessment indicators included seeds/seedlings, plowing, sowing/transplanting, field management, and harvesting. The costs of the different plantation modes were evaluated using a multi-criteria analysis (MCA) method [27,28]. The following method was developed to calculate the MCA scores (ranging from 0 to 100):

\[
S_{\text{cost}} = \sum \left( \frac{H}{H_{\text{max}}} \times W \right) \times 100
\]

where \(H, H_{\text{max}},\) and \(W\) represent the input value, the maximum value, and the weight of each indicator, respectively. \(S_{\text{cost}}\) represents the assessment cost score.

2.5. Statistical Analyses

The results of all the experiments are presented as arithmetic means with standard errors. Differences between the means were statistically analyzed using IBM Statistical Package for the Social Sciences Statistics 26 for variance analysis. The figures were created using the ArcGIS 10.7, Origin Pro 2021 (9.8.0.200), and Adobe Illustrator 2021 (25.0).

3. Results

3.1. Biomass and Yield of Rapeseed with Cd/Pb Exposure

The per plant biomass, yield, seed yield, and straw yield of each rapeseed cultivar ranged from 62.96 to 102.09 kg·hm\(^{-2}\), 6155.47 to 12,217.03 kg·hm\(^{-2}\), 1960.33 to 4010.21 kg·hm\(^{-2}\), and 3228.40 to 8525.60 kg·hm\(^{-2}\), respectively (Figure 1). Among the 15 rapeseed cultivars, QY-10 had the lowest yield (6155.47 kg·hm\(^{-2}\)) and SY-123 had the highest yield (12,217.03 kg·hm\(^{-2}\)) (Figure 1B). The top six cultivars for each index all belonged to \(B.\ napus\).

![Figure 1. Biomass per plant (A), yield (B), seed yield (C), and straw yield (D) of the 15 rapeseed cultivars (Mean ± SE, n = 3). Different lowercase letters indicate a significant difference among the 15 rapeseed cultivars (p < 0.05).](image-url)
3.2. Cd/Pb Concentrations in Rapeseed Tissues

The Cd concentrations in the roots, stems, pods, and seeds ranged from 0.10 to 0.35 mg·kg⁻¹, 0.18 to 0.69 mg·kg⁻¹, 0.11 to 0.54 mg·kg⁻¹, and 0.12 to 0.64 mg·kg⁻¹, respectively (Figure 2A). *B. campestris* SYH and ZS100 had significantly higher Cd concentrations in each tissue than the other *B. napus* cultivars.

The Pb concentrations of the rapeseed roots, stems, pods, and seeds ranged from 0.29 to 1.31 mg·kg⁻¹, 0.21 to 1.38 mg·kg⁻¹, 0.50 to 1.74 mg·kg⁻¹, and 0.49 to 1.22 mg·kg⁻¹, respectively (Figure 2B). The amount of Pb absorbed by the pods of most of the rapeseed cultivars was noticeably higher than that absorbed by their roots and seeds. The Pb concentration in the stem of *B. campestris* ZS100 was the highest, reaching 1.38 mg·kg⁻¹, and that in the pods and seeds of ZS100 were also at higher levels among the 15 cultivars.

![Figure 2](image_url)

**Figure 2.** Cd (A) and Pb (B) concentrations in the roots, stems, pods, and seeds of the different rapeseed cultivars (Mean ± SE, n = 3). The diagonal line on the column represents *B. campestris*. The “*“ symbol indicates statistically significant differences in the same tissues among the 15 rapeseed cultivars (p < 0.05).

3.3. Cd/Pb Accumulation and Translocation

The BCFs for Cd and Pb of the 15 rapeseed cultivars were all less than 1.00 (Figure 3A,B). The BCFs of Cd in the ZS100 pods and seeds reached 0.260 and 0.220, respectively, which was significantly greater than those in the other cultivars. The BCFs of Pb in the rapeseed tissues ranged from 0.0011 to 0.0091. In general, the BCFs of Pb of all the stems studied, except for ZS100, were lower than those of the roots, pods, and seeds.

The TF results are shown in Figure 3C,D. The Cd-TF₁ and Cd-TF₂ values ranged from 0.86 to 6.33 and 0.34 to 1.20, respectively. Except for SY-092, where the Cd-TF₁ was 0.86,
the Cd-TF₁ was higher than 1.00 for the other rapeseed cultivars. Only the Pb-TF₁ values of ZY-821 and ZS100 reached 1.25 and 2.53, respectively. All the other Pb-TF₁ values were less than 1.00. However, Pb-TF₂ was significantly higher than Pb-TF₁, ranging from 0.54 to 4.53 for the different rapeseed cultivars.

Figure 3. BCFs of Cd (A) and Pb (B) of the different rapeseed cultivars (Mean ± SE, n = 3). TFs of Cd (C) and Pb (D) of the different rapeseed cultivars (Mean ± SE, n = 3). TF₁ indicates the transfer factor of roots to stems. TF₂ indicates the transfer factor of stems to pods and seeds. The diagonal lines on the column represent B. campestris. Different lowercase letters indicate significant differences among the 15 rapeseed cultivars (p < 0.05).

3.4. Rapeseed Oil/Meal Quality Assessment
Considering that no standard exists for Cd in fats in the national standard GB2762-2022 [29], we used the Cd level (0.002 mg·kg$^{-1}$) of two types of refined rapeseed oil purchased from the market as the reference, where the HMs concentration was strictly tested. The Cd concentrations of the rapeseed oil of the 15 cultivars studied were all less than the reference at 0.002 mg·kg$^{-1}$. The Pb concentration of the rapeseed oil (Table 2) was lower than the limit value (0.1 mg·kg$^{-1}$) specified in the National Food Safety Standard Limit of Pollutants in Food of China (GB2762-2022) [29]. In addition, the amounts of Cd and Pb in the rapeseed oil of the 15 rapeseed cultivars were undetectable (Cd 0.002 mg·kg$^{-1}$, Pb 0.001 mg·kg$^{-1}$) after SEB treatment.

There are no reference standards for rapeseed meal Cd and Pb concentrations in the Feed Hygiene Standard; therefore, the Cd concentration refers to the standard for plant feed raw materials, and the Pb concentration refers to the standards for other feed raw materials. The Cd and Pb concentrations in the rapeseed meal were lower than 0.790 and 2.651 mg·kg$^{-1}$, respectively, and were within the limits defined in the relevant standards.

Quality inspections, including the oil, oleic acid, glucosinolate, erucic acid, and protein contents of the rapeseed oil from the 15 cultivars, are presented in Table S2. According to the rapeseed (GB/T11762-2006) standard in China [30], the erucic acid content standard was set at 3%, and the glucoside content standard was set at 35% for low-erucic acid and low-glucoside rapeseed. Among the 15 cultivars, SY-195, FY-10, SY-123, and SY-8 met the quality standards for the low-erucic acid and low-glucoside rapeseed.

### Table 2. Cd and Pb concentrations in rapeseed oil and meal (mg kg$^{-1}$).

<table>
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<th>Cultivars</th>
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<th>Oil Pb</th>
<th>Meal Cd</th>
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</table>

1 MP: mechanical pressing technology. 2 SBE: subcritical low-temperature butane extraction technology.

National Food Safety Standard Limit of Pollutants in Food (GB2762-2022) [29]

Rapeseed oil in the market

Feed Hygiene Standard (GB13078-2017) [31]

Organic Fertilizer Standard (NY525-2012) [32]
3.5. Cd/Pb Extraction Amount

Figure 4 depicts the amounts of HMs extracted from the 15 rapeseed straw samples. The Cd and Pb extraction amounts of the one-year winter rapeseed plantation ranged from 1.01 to 4.54 g·hm\(^{-2}\) and 1.32 to 11.59 g·hm\(^{-2}\), respectively. A cluster analysis showed that the two rapeseed cultivars with the best extraction capacities were ZS100 and SY-123 for both Cd and Pb, which belong to \(B.\ campestris\) and \(B.\ napus\), respectively. Additionally, ZS-7 and QY-1 extracted the lowest amounts of Cd and Pb, respectively.

![Figure 4](image)

**Figure 4.** The Cd (A) extraction amount and Pb (B) extraction amount in the straw of 15 rapeseed cultivars (Mean ± SE, \(n = 3\)). Different lowercase letters indicate significant differences at the 0.05 level.

4. Discussion

4.1. Differences in the Yield and HMs Accumulation among the 15 Winter Rapeseed Cultivars

The degree of soil contamination and cultivar diversity greatly influence the yield of rapeseed [33]. At the Tangshi remediation base, the 15 winter rapeseed cultivars successfully overwintered and completed their life cycles, indicating that they had some resistance to Cd and Pb contamination [34]. Compared to the conventional yield data presented in Table 1, the seed yield of 11 rapeseed cultivars decreased, whereas that of the other four cultivars increased. Normally, high concentrations of Cd or Pb in the soil can reduce chlorophyll content and photosynthetic efficiency, leading to a decrease in the root growth and stem biomass of rapeseed, and further limiting the rapeseed yield [35,36]. Amirahmadi et al. found that Cd-contaminated soil has a negative impact on maize growth and nutritional characteristics [37]. Wang et al. found that Cd affected the growth...
of the above-ground parts of rice, resulting in lower plant height and obvious wilting and necrosis of the leaves [38]. However, some research results have also shown that Cd or Pb in the soil may stimulate plants to develop a compensation mechanism and activate antioxidant enzymes [39]. Su et al. found that when the Pb stress was 200 mg·L\(^{-1}\) and 400 mg·L\(^{-1}\), the biomass of Koelreuteria paniculata increased by 123.8% and 112.7%, respectively, and the activity of catalase (CAT) and peroxidase (POD) increased first and then decreased with a rise in Pb level [40]. The higher yields of the four rapeseed cultivars may be attributable to the stimulation of the stress resistance response by HMs and the encouragement of rapeseed growth. Moreover, rapeseed can counteract harmful effects through various physiological and biochemical pathways, such as the barrier effect of rhizosphere microorganisms, the scavenging of excessive superoxide radicals by antioxidant systems [15,41], the compartmentalization of subcellular compartments [42], and the chelating effects of phytoalexins [43,44].

Researchers have found that different genes among rapeseed cultivars are key factors leading to the diversity in HMs tolerance and regulatory abilities [45]. Bai et al. designed primers based on genomic data to amplify three PCS genes in rapeseed and to drive the overexpression of these three genes. The results showed that the discovery could significantly improve plant tolerance to Cd stress [46]. Miyadate et al. identified heavy metal ATPase 3 (OshMA3) as the gene that controls root-to-shoot Cd translocation rates [47]. According to Figure 3, the BCFs of Cd of B. campestris were higher than that of B. napus, indicating that B. campestris had a higher Cd accumulating capacity. Cd and Pb can be activated and absorbed by a well-developed root system and transported over short distances through the symplastic and apoplastic pathways of rapeseed [16]. Chen et al. used RNA sequencing to analyze the root samples of B. napus, B. campestris, and B. oleracea under Cd stress, and discovered 109 potential Cd-related genes, including 67, 33, and 29 in B. napus, B. campestris, and B. oleracea, respectively [48]. Through the amplification and transcription of related genes, a large number of transporters are produced and transport HMs from the roots to the shoots through the xylem or phloem over long distances [49,50]. The diversity in transporter genotypes and expression between B. napus and B. campestris may be an important reason for the differences in HMs accumulation [46]. Our study also found that B. campestris rapeseed cultivars were short, with more fibrous roots and lower yields, whereas the B. napus cultivars were tall, with more branches and higher yields. The flourishing root structure of B. campestris may be the other key reason for its strong capacity to accumulate Cd and Pb.

In most cases, plants reduce Cd toxicity by increasing Cd chelation onto the root cell wall components or by retaining it in the vacuoles of the roots; thus, the roots have the highest concentration of HMs [51,52]. However, in this study we discovered that the accumulation of Cd and Pb in the seeds was substantially higher, with Pb accumulating more than Cd. According to recent research, in places with no appreciable changes in soil characteristics and HMs concentrations, a significant increase of 293% in Pb accumulation in grains under air deposition has been detected [53]. Some researchers have indicated that atmospheric Pb can enter plants through the stomata on leaves, where it can subsequently travel to the grains [54,55]. Ouyang et al. chose cadmium sulfide (CdS) to simulate atmospherically deposited Cd, and found that CdS nanoparticles entered bok choy (B. chinensis) leaves through the stomata [56]. Ma et al. discovered that wheat leaves and spikes may have directly contributed to wheat grains Pb contamination absorbed from the atmosphere [57]. Furthermore, freshly settled HMs were more prone to gather in surface soils, significantly increasing their bioavailability [58–60]. Therefore, the atmospheric deposition of HMs caused by nearby smelting enterprises may be a key factor for the significant increase in HMs in the seeds of rapeseed.

4.2. Risk Assessment of Oil and Safe Utilization of Oil Residues and Straw

Winter rapeseed accounts for approximately 50% of the national self-produced edible oil in China [61]. Rapeseed oil is extracted using the local traditional mechanical pressing
technique, according to the small-workshop oil pressing conditions in Jiyuan. The subcritical low-temperature butane extraction technique was used to compare the aforementioned method to advanced technologies. The Cd and Pb concentrations in the crude oil did not show considerable differences compared to the rapeseed oil purchased in the market. And the Pb concentration in the crude oil was lower than the limit stipulated in the standard GB2762-2022 [29]. In general, the HMs content of rapeseed oil was significantly reduced after oil extraction [62]. On the one hand, interactions between the proteins and amino acids in rapeseed meal and the HMs reduced the quantities of HMs in the rapeseed oil [13,14]. Moreover, both Cd and Pb concentrations were lower in SBE oil than in MP oil; this result may be explained by the fact that SBE technology has an outstanding capacity to extract fatty acids by organic solvent butane, and decreases the dissolution of HMs and other impurities in seeds. However, MP technology uses simple external forces to cause tissue crushing and produce oil, making it easier for HMs to remain in the oil [62].

The results of the health risk assessment of Cd and Pb in rapeseed oil show that the CRs of Cd for adults and children were both within the acceptable range defined by the USEPA. Similarly, the HQs of Pb were within the risk limits (1.00). The CR and HQ statistics indicated that despite the soil in the Tangshi area having higher than standard levels of Cd and Pb, the exposure level of rapeseed oil produced by MP or SBE technologies would not cause obvious carcinogenic or non-carcinogenic risks to the human body [63], and rapeseed oil can safely enter the market for consumption. Children may be more susceptible to HMs contamination because their CRs and HQs are higher than those of adults [64].

Rapeseed meal and straw can also be safely disposed of or effectively utilized. Rapeseed meal is an important feed protein source, second only to soybean meal [65]. The presence of adequate amino acids makes it a suitable organic fertilizer material to enhance soil moisture retention and provide nutrients for crops [2]. Fifteen different types of rapeseed meals were found to have Cd and Pb concentrations that were below the limits in the Chinese national standards (GB13078-2017, NY525-2012) [31,32]; therefore, they can be utilized as organic fertilizers or feed ingredient resources.

One way to dispose of straw is to return it to the field. The Cd and Pb concentrations of the 15 types of rapeseed straw were lower than the limits outlined in NY525-2012. In addition, Nie et al. demonstrated that long-term straw return did not immediately result in significant Cd accumulation [66]. Rapeseed straw is rich in fiber substances and nutrient elements, such as nitrogen, carbon, phosphorus, and potassium, which can effectively improve the soil nutrient content and organic matter [67]. Another method of straw disposal is to remove straw from the field and treat it harmlessly. The highest Cd and Pb extraction amounts were 4.54 and 11.59 g·hm⁻² from ZS100, respectively (Figure 4). Based on a topsoil analysis (0–20 cm), soil Cd and Pb can be decreased by 0.0069 and 0.0022% per year by removing straw, respectively. The screening and optimizing of plants with HMs tolerance and high economic value is currently an ideal strategy for soil remediation [68]. Compared to the extraction efficiency of the hyperaccumulator (50–300 g·hm⁻²·a⁻¹), the remediation effect of straw removal is still insufficient [69]. However, compared to wheat cultivation, rapeseed cultivation solves the problem of HMs exceeding the standard in wheat grains; in addition, rapeseed straw accumulates more HMs than wheat, resulting in a higher extraction amount [69].

4.3. Profit Analysis and Comprehensive Assessment of Rapeseed–Maize Rotation

Costs were calculated to evaluate the benefits of rapeseed, maize, and wheat cultivation. Considering that the 15 rapeseed cultivars had various drought/disease/insect resistance characteristics and seed quality, leading to differences in the costs of irrigation, pesticides, and unit prices, this result was based on the average planting cost and the market average price. A cost analysis was conducted based on five aspects: seed/seedlings, plowing, sowing/transplant, field management, and harvesting (Figure 5A). The detailed costs are listed in Table S4. The cost analysis results show the following pattern: wheat
(11,850 CNY·a⁻¹·hm⁻²) > rapeseed (11,100 CNY·a⁻¹·hm⁻²) > maize (10,350 CNY·a⁻¹·hm⁻²). Additionally, the evaluation results of the multi-criteria analysis (MCA) method regarding the cultivation cost of the three crops show that wheat planting had the highest cost score at 100, followed by rapeseed (94.52) and maize (86.35) (Figure 5B).

Combined with the maize, wheat, and rapeseed yield and price data from the China Statistical Yearbook (2021), the normal annual profits of rapeseed, maize, and wheat cultivation were 8900, 6650, and 10,650 CNY·a⁻¹·hm⁻², respectively. According to previous research, HMs in wheat in the Tangshi area exceeded the standard and endangered the food safety for local residents [11]. In our team’s preliminary study, four years of continuous monitoring found that despite the existence of atmospheric deposition, HMs concentrations in soil did not increase significantly, and planting rapeseed can realize safe production [69]. When wheat cannot enter the market due to excessive HMs in the seeds, the alternative planting technology of winter rapeseed may be appropriate; a rapeseed–maize rotation yielded a profit of 15,550 CNY·a⁻¹·hm⁻², which was 133.8% higher than the monoculture maize model. Rapeseed plantations, compared to wheat cultivation, have the potential to significantly lower the environmental impacts of HMs, while also improving the economic output by 35.5 to 123.5%, according to Guo et al. [69]. The alternative planting technology of winter rapeseed not only ensured the food safety of crops, but also reduced the content of HMs in the soil by removing straw from the field [70,71]. This can eliminate the vigilance of local residents in planting crops, increase the planting area of crops and cash crops, and improve the incomes of farmers.

Rapeseed yield determines the benefits of rapeseed cultivation [72,70]. Improving oil quality is a key factor in increasing market competitiveness [73]. The yield and quality determine whether rapeseed cultivation can achieve a successful extension of applications [74]. The profit data of the 15 cultivars in Figure 5C show that ZY-821, SY-092, YY-2, SY-195, and ZS-7 had higher economic benefits. The biomass, seed yield, profit, erucic acid content, glucosinolate content, oil content, oleic acid content, and protein content of the 15 rapeseed cultivars were integrated using cluster analysis (Figure 5D). The results show that B. campestris SYH and ZS100 and B. napus ZY-821 had the highest comprehensive benefits and were suitable for planting in Cd- and Pb-contaminated farmland. In addition, rapeseed cultivation technology is relatively mature. Local farmers are experienced in planting rapeseed, and the equipment for rapeseed seeding and harvesting machinery is well established [75]. Therefore, rapeseed cultivation technology is feasible on a large scale, and can effectively achieve safe utilization while also increasing the economic output in HMs-contaminated farmlands affected by atmospheric deposition.
Figure 5. (A) Annual cost structures of rapeseed, maize, and wheat cultivation. (B) Cost scores of rapeseed, maize, and wheat cultivation. (C) Annual revenues of the 15 rapeseed cultivars. (D) Cluster analysis of the yield, oil quality, and net benefit of the 15 cultivars of rapeseed. The index values from 1 to 8 represent the biomass, seed yield, net benefit, oil content, oleic acid content, protein content, erucic acid content, and glucosinolate content, respectively.

5. Conclusions

In this study, we conducted a large-scale planting experiment with 15 winter rapeseed plants on farmlands in typical HMs deposition areas around smelting enterprises in northern China. This study reveals that *B. napus* absorbed lower levels of HMs and grew better. The Pb concentration in the seeds was much higher than that of Cd, and atmospheric deposition was a risk source for both Cd and Pb. The Cd and Pb concentrations in the oil and meal conformed to the national standards, and they can be used as edible oil and feed or fertilizer, respectively. Additionally, *B. campestris* SYH and ZS100 and *B. napus* ZY-821 had the highest comprehensive benefits; winter rapeseed–maize rotation could effectively reduce environmental risks while also increasing economic output by 133.8%. In conclusion, the highly efficient and safe utilization of farmlands contaminated with Cd and Pb around smelting enterprises can be achieved using winter rapeseed cultivation.

Rapeseed planting technological maturity and economic viability were thoroughly assessed in this study. SYH, ZS100, and ZY-821 rapeseed cultivars, which have low heavy metal accumulation and high rapeseed oil quality, can be popularized and widely planted on cadmium–lead polluted fields.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su151511750/s1, Figure S1: Field trial locations; Figure S2: Annual Cd (A) and Pb (B) depositions in atmospheric dust; Table S1: Fundamental physicochemical characteristics of the soil in the Tangshi test area; Table S2: Quality inspection of the rapeseed oil of
the 15 cultivars; Table S3: Chemical carcinogenic and non-carcinogenic risk assessments of rapeseed oil; Table S4: Detailed costs of rapeseed, maize, and wheat plantation.

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