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Filter Cake Biochar Reduces Cadmium Bioavailability and Accumulation in Vegetables Grown in Contaminated Soil

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ABSTRACT

Cadmium (Cd) contamination in agricultural soils poses serious risks to food safety and human health, particularly in regions with acidic soils that favor metal mobility. This study evaluated the effectiveness of filter cake biochar (FCB) in remediating Cd-contaminated soil and mitigating its transfer to vegetables. A greenhouse experiment was conducted using an Ultisol contaminated with 10 mg kg^{-1} Cd. Four vegetables, Swiss chard (*Beta vulgaris*), okra (*Abelmoschus esculentus*), beetroot (*B. vulgaris*), and bell pepper (*Capsicum annuum*), were cultivated in pots with and without FCB amendment. FCB application reduced Cd availability in soil, from 4.5 to 0.5 mg kg^{-1}, bringing concentrations below the regulatory guideline (1.3 mg kg^{-1}). This was accompanied by a reduction of up to 87% in Cd concentrations in plant tissues. Improvements in soil fertility were also observed, including increased pH, organic carbon, and availability of P, Ca, Mg, Fe, and Mn. Cd accumulation in plant tissues varied by species, with bell pepper showing the lowest and Swiss chard the highest concentrations. Crucially, only vegetables cultivated in FCB-amended soil yielded edible produce, underscoring the biochar's role in mitigating phytotoxicity and enabling safe consumption. In addition to lowering Cd uptake, FCB enhanced biomass and nutrient accumulation in shoots. Correlation analysis confirmed strong positive relationships between soil fertility parameters and plant nutrient uptake, and negative correlations between Cd availability and plant performance. These results demonstrate that FCB is an effective strategy for reducing Cd risks in contaminated soils and improving the productivity and safety of vegetable crops.

1 | Introduction

Cadmium (Cd) contamination in agricultural soils is a pervasive global challenge, impacting millions of hectares and posing severe threats to food security and human health. Due to its nondegradable nature, Cd persists in soils and causes long-term damage [1, 2]. Improper disposal of industrial waste, mining activities, poor agricultural practices, such as the uncontrolled application of pesticides and fertilizers, as well as the use of contaminated irrigation water, are major contributors to elevated Cd concentration in agricultural soils [1, 3]. The consequences of this contamination go beyond immediate impacts, also threaten-

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ing the sustainability of food production systems [2, 4]. This is particularly relevant in tropical regions, where naturally acidic soils enhance metal mobility.

The intake of Cd-contaminated food can lead to severe health complications. Cd exposure is notably linked to *itai-itai* disease and is known to replace calcium in the body, leading to its accumulation in bones and causing bone softening [5]. Additionally, Cd has been classified as an endocrine disruptor [6], contributing to hormonal imbalances. Chronic Cd toxicity may also impair the absorption of micronutrients such as copper (Cu) and iron (Fe), resulting in conditions such as anemia and weakened immune response [7].

In addition to its harmful effects on higher organisms, Cd contamination degrades soil quality. Cd toxicity can reduce both microbial and root biomass, disrupting critical nutrient cycles such as those of nitrogen and phosphorus [8]. These effects are particularly pronounced in tropical soils, which are typically acidic and favor greater Cd and other heavy metals bioavailability [3, 9]. Consequently, Cd-contaminated soils require remediation to ensure soil and ecosystem health. Among the various remediation approaches, immobilization using biochar has shown considerable promise.

Biochar, a carbon-rich material produced through the pyrolysis of biomass, often from underutilized residues such as rice straw and sewage sludge, acts as a sorbent that reduces Cd availability in the soil. Its effectiveness is attributed to several mechanisms, including surface adsorption within its porous structure (which physically traps Cd ions), complexation with functional groups (which binds Cd through chemical interactions), and precipitation of Cd into less soluble forms [10], which reduces its mobility and bioavailability. Beyond immobilizing heavy metals, biochar enhances nutrient availability, stimulates microbial activity, and improves soil water retention, factors that collectively support better plant development [11–14].

When vegetables, especially leafy greens and root crops, are cultivated in Cd-contaminated soils, they may accumulate the metal and become a direct pathway for human exposure. As Cd uptake varies by species and plant part, accumulating in leaves, stems, or tubers depending on the crop, it is essential to monitor such vegetables to assess the health risks posed by consumption of their edible portions [2, 4, 9, 15–17].

Given that Cd is readily taken up by crops, especially root and tuber species that grow in direct contact with contaminated soils and water, there is a critical need for simple technologies to reduce its bioavailability and prevent its transfer into the food chain. This study aims to evaluate the effectiveness of filter cake biochar (FCB) in remediating Cd-contaminated soils, focusing on reducing Cd bioavailability and mitigating its transfer to the food chain through vegetable cultivation. Additionally, the study explores how FCB influences soil quality, particularly nutrient dynamics and plant growth, to promote food safety. We hypothesized that FCB application would reduce Cd bioavailability and plant uptake across different vegetable species, while simultaneously improving soil fertility and crop productivity under contaminated conditions.

TABLE 1 | Characterization of Cd-contaminated soil used in the experiment.

Variable	Unity	Mean	±S.D.
pH	H_2O (1:2.5)	5.28	0.01
Ca^{2+}	$cmol_c\ dm^{-3}$	3.97	0.06
Mg^{2+}	$cmol_c\ dm^{-3}$	0.5	0.06
Al^{3+}	$cmol_c\ dm^{-3}$	0.13	0.03
Na^{+}	$cmol_c\ dm^{-3}$	0.83	0.05
K^{+}	$cmol_c\ dm^{-3}$	0.38	0.01
H + Al	$cmol_c\ dm^{-3}$	3.57	0.13
CEC	$mmolc\ dm^{-3}$	70.46	8.56
Available P	$mg\ dm^{-3}$	92.19	5.35
SOC	$g\ kg^{-1}$	13.13	0.45
SOM	$g\ kg^{-1}$	22.64	0.77
Cd	$mg\ kg^{-1}$	3.91	0.14
Sand	$g\ kg^{-1}$	628	56.52
Silt	$g\ kg^{-1}$	32	3.2
Clay	$g\ kg^{-1}$	340	23.8

Abbreviations: Cd, available cadmium extracted with 0.01 mol L^{-1} $CaCl_2$; CEC, cation exchange capacity; SD, standard deviation; SOC, soil organic carbon; SOM, soil organic matter.

2 | Materials and Methods

2.1 | Soil Analyses and Cd-Induced Contamination Procedures

A pot experiment was designed to evaluate the cultivation of vegetables in Cd-contaminated soil treated with FCB. The soil was an Ultisol, collected from the 0 to 20 cm depth layer. The soil was air-dried, homogenized, crushed, and sieved through a 4.0-mm mesh for use in the experiment. A subsample was further sieved through a 2.0-mm mesh and used for chemical and physical characterization (Table 1).

Particle size distribution was determined using the Bouyoucos hydrometer method after chemical dispersion with NaOH and agitation for 16 h. Soil pH was measured in water at a 1:2.5 (v/v) ratio. Exchangeable Na^+ and K^+ were extracted using Mehlich-1 solution and quantified by flame photometry. Exchangeable Ca^{2+} and Mg^{2+} were extracted with 1.0 mol L^{-1} KCl solution and determined by complexometric titration with 0.0125 mol L^{-1} EDTA. Exchangeable Al^{3+} was also extracted with 1.0 mol L^{-1} KCl and quantified by titration with 0.025 mol L^{-1} NaOH. Potential acidity was determined by extraction with 0.5 mol L^{-1} calcium acetate followed by alkaline titration. Available phosphorus (P) was extracted using Mehlich-1 and determined colorimetrically. Soil organic carbon (SOC) was measured using the wet oxidation method of Walkley–Black [18]. Cation exchange capacity (CEC) was determined following the sodium/ammonium acetate method [19].

For induced contamination, Cd chloride ($CdCl_2 \cdot H_2O$) was added to the soil to reach a concentration of 10 mg kg^{-1} Cd. After

spiking, the soil was incubated for 30 days to allow equilibration. This dose was selected on the basis of the study by Cunha et al. [20], which reported a 30% reduction in maize biomass at this Cd level, indicating its suitability for assessing the effectiveness of biochar under toxic Cd concentrations. Although specific reference data for the vegetable species used in this study are lacking, maize is widely recognized as a sensitive indicator plant for heavy metal stress, making it a valid benchmark for establishing contamination levels in phytotoxicity studies.

To determine the available Cd in the soil after treatment, samples were extracted using 0.01 mol L^{-1} $CaCl_2$. For this, 30 mL of the solution was added to 3.0 g of soil and shaken at 60 rpm for 16 h. The suspensions were then centrifuged at 4000 rpm for 20 min, and the supernatants were filtered through membranes with a pore size <2 μm. Cd concentrations were determined by inductively coupled plasma optical emission spectrometry (ICP-OES, Perkin Elmer 7000 DV).

2.2 | Biochar Production

The feedstock used for biochar production was filter cake, a by-product of sugarcane juice filtration in the sugar industry. This material is considered an excellent feedstock for biochar due to its high content of organic matter and nutrients, easy availability, and low cost. The filter cake was collected from a sugar mill located in the Pernambuco State, Brazil. FCB was produced via slow pyrolysis, in which the material is pyrolyzed at 400°C for 6 h. At this temperature range, the process favors the production of solid biochar [21]. A homemade fixed-bed furnace was used for pyrolysis, which operates under limited oxygen conditions and allows for relatively uniform heat distribution. The design ensures consistent pyrolysis temperature and residence time, both of which are critical for determining the physicochemical properties of the resulting char.

Subsamples of the FCB were collected in triplicate, oven-dried at 40°C, ground, and sieved through an 850 μm mesh (Table 2). Characterization was conducted following the methodologies proposed by Singh et al. [22], as follows: pH and electrical conductivity (EC) were measured from the same extract, prepared using a 1:5 (v/v) suspension in distilled water. Moisture was determined gravimetrically after drying for 24 h at 105°C. Volatile matter was determined from samples previously dried at 105°C; triplicate subsamples (1.0 g) were weighed into crucibles and heated in a muffle furnace at 750°C for 6 h. Fixed carbon content was calculated as the difference between dry matter, volatile matter, and ash content.

For elemental analysis (Table 2), 0.2 g of FCB (in triplicate) was digested with 8 mL of HNO_3 and 2 mL of H_2O_2 in Teflon tubes using a microwave digestion system at 180°C for 10 min. The resulting extracts were filtered through slow-flow blue-band filter paper and diluted to 25 mL with ultrapure water in certified volumetric flasks [23]. Phosphorus was determined colorimetrically, potassium (K) and sodium (Na) by flame photometry, calcium (Ca), magnesium (Mg), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and Cd concentrations were determined by ICP-OES.

TABLE 2 | Mean values (±standard deviation) of the characteristics of the filter cake biochar used in the experiment (dry basis).

Variable	Unit	Mean	±SD
pH	H_2O (1:5)	7.9	0.1
EC	dS m	456	60.4
CEC	$cmol_c\ dm^{-3}$	225	11.6
SA	$m^2\ g^{-1}$	185	15.7
Humidity	%	6	0.2
Fixed carbon	%	56	9.8
Ashs	% (m m^{-1})	20.4	1.3
Carbon	% (m m^{-1})	84	2.5
Nitrogen	% (m m^{-1})	4	0.9
Oxigen	% (m m^{-1})	9.2	1.7
Phosphorus	g kg^{-1}	69.5	2.1
Cadmium	mg kg^{-1}	<LOQ	<LOQ

Abbreviations: CEC, cation exchange capacity; EC, electrical conductivity; LOQ, limit of quantification (0.07 mg kg^{-1} Cd); SA, specific surface area; SD, standard deviation.

2.3 | Greenhouse Experiment Setup

The experiment was conducted in a greenhouse using a Cd-contaminated Ultisol fertilized with the following nutrient rates: N, P, K, and S were applied at rates of 250.0, 240.0, 150.0, and 160.0 mg kg^{-1} of soil, respectively, supplied through $(NH_4)_2SO_4$, $NH_4H_2PO_4$, and KNO_3. For micronutrients, the applied rates were Fe 2.0 mg kg^{-1}, Mn 4.0 mg kg^{-1}, B 1.0 mg kg^{-1}, and Mo 0.2 mg kg^{-1}, using $FeSO_4{\cdot}7H_2O$, $MnCl_2{\cdot}4H_2O$, H_3BO_3, and $Na_2MoO_4{\cdot}2H_2O$, respectively. Additionally, biochar derived from filter cake was incorporated into the soil at a 5% (w/w) rate.

Four vegetable species were selected for the experiment: Swiss chard (*Beta vulgaris* L. var. cicla L.), okra (*Abelmoschus esculentus* (L.) Moench), beetroot (*B. vulgaris* L.), and bell pepper (*Capsicum annuum* L.), chosen due to their different edible plant parts (leaves, fruits, and tubers). For initial development, seeds were sown in expanded polystyrene trays filled with inert commercial substrate. The trays were kept in the greenhouse and irrigated daily. Once the seedlings developed definitive leaves, approximately 10 days after sowing, they were transplanted into pots containing 5 kg of soil. Plants were irrigated daily to maintain soil moisture at approximately 80% of field capacity. The experiment was conducted in a completely randomized design with a 4 × 2 factorial arrangement, consisting of four vegetable species and two Cd doses, with three replicates per treatment.

2.4 | Harvest and Plant Tissue Analysis

Vegetables were harvested as they reached their physiological maturity. The edible parts were separated from the remaining aboveground structures (when applicable), and roots were carefully removed from the soil. Plant material was taken to the laboratory, rinsed with distilled water, and dried in a forced-air

oven at 70°C until constant weight. After drying, the samples were weighed to determine dry matter content and ground in a Wiley-type knife mill.

For nutrient composition and determination of Cd concentrations in plant tissues, 0.500 g of root and shoot samples were weighed and transferred to Teflon digestion tubes containing 8 mL of HNO_3 and 2 mL of H_2O_2. Digestion was performed in a microwave oven (Milestone—Ethos Easy) at 180°C for 10 min [23]. The resulting extracts were filtered through quantitative blue-band filter paper (pore size <2.0 μm) and brought to a final volume of 25 mL with ultrapure water in certified volumetric flasks. In the digestion extracts, P was determined calorimetrically, whereas Ca, Mg, Fe, Mn, Cu, Zn, and Cd were quantified using ICP-OES.

2.5 | Soil Sampling and Analysis

At harvest, soil samples were collected from each pot. Samples were air-dried, crushed, and sieved through a 2-mm mesh. The extraction of available Cd from the soil followed the method proposed by Yin et al. [24], in which 3.0 g of soil were mixed with 30 mL of 0.01 mol L^{-1} $CaCl_2$ solution and shaken for 16 h at 60 rpm. After shaking, the suspensions were centrifuged at 4000 rpm for 20 min. The resulting extracts were filtered through quantitative blue-band filter paper (pore size <2.0 μm). Cd concentrations were determined by ICP-OES. Other soil parameters, including pH, available P, exchangeable Ca, Mg, and Al, total carbon, and CEC, were analyzed using the methods described by Teixeira et al. [18] and Mcgeorge [19], as previously detailed.

2.6 | Quality Control and Statistical Analysis

For quality control of the chemical analyses, blanks and certified reference materials were used: SRM 2711a (Montana Soil) for soil and SRM 1570a (Spinach Leaves) for plant tissues, with certified element concentrations provided by the National Institute of Standards and Technology (NIST). Element recoveries for SRM 2711a ranged from 85% to 105%, whereas recoveries for SRM 1570a were between 90% and 110%. All analyses were performed in duplicate.

Mean values and standard deviations were calculated for all measured variables. Data normality was assessed using the Shapiro–Wilk test. When necessary, data were log- or square root-transformed to meet the assumptions of normality. All variables were subjected to analysis of variance (ANOVA), followed by Tukey's test ($p < 0.05$) for mean comparison. All statistical analyses were performed using the Statistica software (StatSoft Inc., USA).

3 | Results and Discussion

3.1 | Effectiveness of Biochar in Reducing Contamination

Following the application of 5% FCB, the available Cd concentration in the soil decreased from approximately 4.5 mg kg^{-1} to about 0.5 mg kg^{-1} across all vegetable species (Figure 1a). Thus, FCB application successfully reduced soil Cd levels below the agricultural soil threshold of 1.3 mg kg^{-1} established by Brazilian legislation [25], demonstrating its potential as an effective remediation strategy under such contamination conditions.

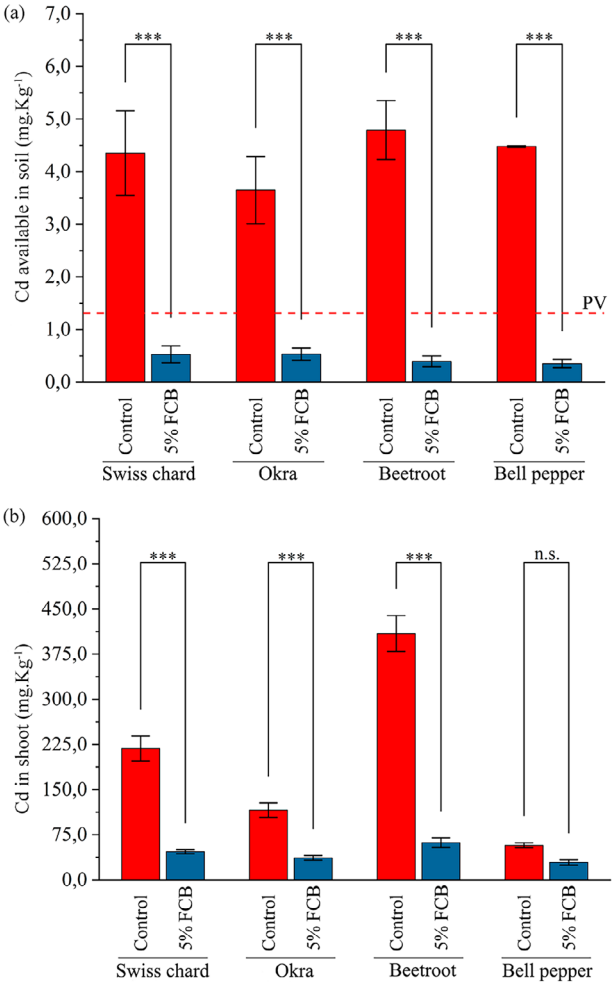


FIGURE 1 | Mean values (±standard deviation) of Cd availability in soil (a) and Cd concentrations in the aerial parts of vegetables (b) grown in Cd-contaminated soil treated with 5% filter cake biochar (FCB). ***: significant at 0.1% probability by Tukey's test, PV: prevention guideline value for Cd in soil (1.3 mg kg^{-1}) according to Conama [25]. Cd, cadmium; FCB, filter cake biochar; ns, not significant.

Several processes can explain the observed reduction in Cd availability in soil. In addition to its high specific surface area, the presence of functional groups, such as hydroxyl, carboxyl, and carbonyl groups, provides effective adsorption sites for available metals, including Cd, onto the biochar structure [3, 10, 26, 27]. Another important mechanism is precipitation. As biochar tends to raise soil pH, Cd may precipitate as insoluble hydroxides, carbonates, or phosphates, thereby reducing its availability [10, 28, 29]. These immobilization mechanisms are particularly relevant in the context of highly contaminated soils, where, in the absence of any amendment, crops are exposed to elevated Cd levels.

Because of the high Cd concentrations in the untreated soil, a substantial accumulation of the metal was observed in the

vegetables under the control treatment (Figure 1b). Cd accumulation reached approximately 400 mg kg^{-1} in beetroot, making it the crop with the highest Cd concentration in both shoots and roots. These values indicate high Cd uptake and highlight the potential risk associated with consuming this crop when grown in contaminated soils. However, when biochar derived from filter cake was applied, the effectiveness of the immobilization mechanisms previously described became evident.

Applying FCB significantly reduced Cd concentrations in the aerial parts of the vegetables, except for bell pepper. Average concentrations decreased to around 50 mg kg^{-1} in Swiss chard, okra, and beetroot, indicating a substantial reduction in Cd uptake by the plants. Veloso et al. [30] reported that applying rice straw biochar at a rate of 30 t ha^{-1} significantly reduced Cd concentration in maize shoots by 34%. This reduction suggests that biochar effectively immobilized Cd in the soil, lowering its bioavailability and, consequently, its accumulation in plant tissues. However, the absence of a significant reduction in Cd uptake in bell pepper suggests that the plant's response to biochar may vary among vegetable species, or that bell pepper possesses intrinsic mechanisms to limit Cd uptake or translocation.

This behavior may be attributed to several factors, including species-specific responses, as well as particular mechanisms of Cd uptake and translocation in bell pepper. Plants absorb Cd from the soil via membrane transporters, and the efficiency and regulation of these transporters can differ between species, resulting in variable metal uptake rates [17, 29]. It is also plausible that bell pepper activates physiological defense mechanisms that allow it to tolerate high Cd concentrations in the soil without necessarily reducing uptake. Such mechanisms may include Cd compartmentalization in cellular vacuoles, production of metal-binding chelators, or activation of antioxidant defense systems [1, 9, 17]. However, further studies on the specific bell pepper cultivar should focus on gene expression analysis of metal transporters or physiological assays for Cd compartmentalization to test this hypothesis.

3.2 | Effects of Biochar on Soil Fertility

Evaluating changes in soil fertility attributes helps to better understand the multifaceted role of FCB in improving soil conditions and promoting healthier plant growth. All soil fertility attributes evaluated were significantly affected by FCB application (Table 3). Across all tested vegetable species (Swiss chard, okra, beetroot, and bell pepper), FCB led to increased soil pH. The initial acidic values, ranging from 4.3 to 4.6, increased to values between 5.7 and 6.2. This rise in pH is a well-known effect of biochar, attributed to its alkaline composition [14, 31]. Moreover, this pH range is considered optimal, as it balances the availability of most plant nutrients, enhancing nutrient uptake by plants while also reducing Cd availability in the soil [14, 31, 32].

The addition of FCB significantly increased SOC levels in all treatments. SOC values in the control treatments ranged from 17.15 to 18.56 g kg^{-1}, whereas in the FCB-treated soils, values ranged from 27.12 to 30.18 g kg^{-1} (Table 3). This increase in SOC is a beneficial effect of FCB application, as the material is

TABLE 3 | Mean values (±standard deviation) of soil fertility attributes in Cd-contaminated soil treated with 5% filter cake biochar (FCB) and cultivated with different vegetable species.

Swiss chard (*Brassica rapa* L.)			
Variable	**Unit**	**Control**	**5% FCB**
pH	—	4.57 ± 0.20a	5.99 ± 0.09b
SOC	g kg^{-1}	18.18 ± 0.69a	28.53 ± 3.53b
Available P	mg dm^{-3}	69.9 ± 25.0a	832.0 ± 98.2b
Available Ca^{2+}	$cmol_c$ dm^{-3}	2.43 ± 0.67a	6.93 ± 0.49b
Available Mg^{2+}	$cmol_c$ dm^{-3}	0.50 ± 0.20a	1.30 ± 0.32b
Available Fe	mg dm^{-3}	44.5 ± 4.3a	102.1 ± 3.1b
Available Mn	mg dm^{-3}	4.17 ± 0.78a	17.53 ± 2.79b
Available Cu	mg dm^{-3}	0.31 ± 0.04a	0.57 ± 0.09b
Available Zn	mg dm^{-3}	6.78 ± 0.76a	11.24 ± 0.72b
Okra (*Abelmoschus esculentus* L.)			
Variable	Unit	Control	5% FCB
pH	—	4.66 ± 0.15a	6.00 ± 0.10b
SOC	g kg^{-1}	18.30 ± 1.41a	28.32 ± 1.13b
Available P	mg dm^{-3}	53.5 ± 5.7a	582.0 ± 120.7b
Available Ca^{2+}	$cmol_c$ dm^{-3}	1.10 ± 0.08a	4.35 ± 0.19b
Available Mg^{2+}	$cmol_c$ dm^{-3}	0.28 ± 0.05a	1.03 ± 0.15b
Available Fe	mg dm^{-3}	62.4 ± 3.6a	97.8 ± 4.2b
Available Mn	mg dm^{-3}	2.01 ± 0.22a	11.53 ± 1.13b
Available Cu	mg dm^{-3}	0.28 ± 0.04a	0.42 ± 0.02b
Available Zn	mg dm^{-3}	4.68 ± 0.23a	7.84 ± 0.15b
Beetroot (*Beta vulgaris* L.)			
Variable	Unit	Control	5% FCB
pH	—	4.41 ± 0.13a	5.72 ± 0.15b
SOC	g kg^{-1}	18.56 ± 0.60a	30.18 ± 2.99b
Available P	mg dm^{-3}	71.7 ± 3.7a	634.4 ± 53.3b
Available Ca^{2+}	$cmol_c$ dm^{-3}	3.53 ± 0.45a	9.28 ± 0.26b
Available Mg^{2+}	$cmol_c$ dm^{-3}	0.80 ± 0.18a	1.85 ± 0.30b
Available Fe	mg dm^{-3}	53.8 ± 3.7a	151.3 ± 13.4b
Available Mn	mg dm^{-3}	6.88 ± 1.33a	21.70 ± 1.40b
Available Cu	mg dm^{-3}	0.30 ± 0.02ns	0.40 ± 0.05ns
Available Zn	mg dm^{-3}	6.01 ± 0.31a	9.05 ± 0.47b
Bellpeper (*Capsicum annuum* L.)			
Variable	Unit	Control	5% FCB
pH	—	4.30 ± 0.04a	6.24 ± 0.17b
SOC	g kg^{-1}	17.15 ± 0.58a	27.12 ± 1.60b
Available P	$cmol_c$ dm^{-3}	2.15 ± 0.10a	6.35 ± 0.52b
Available Ca^{2+}	$cmol_c$ dm^{-3}	0.48 ± 0.10a	1.48 ± 0.05b
Available Mg^{2+}	mg dm^{-3}	70.7 ± 5.7a	101.6 ± 5.0b
Available Fe	mg dm^{-3}	4.09 ± 0.61a	12.80 ± 1.77b

(Continues)

TABLE 3 | (Continued)

Swiss chard (*Brassica rapa* L.)			
Variable	**Unit**	**Control**	**5% FCB**
Available Mn	mg dm^{-3}	0.57 ± 0.05b	0.41 ± 0.01a
Available Cu	mg dm^{-3}	5.30 ± 0.04ns	4.76 ± 0.16ns

Note: Mean values followed by the same letter within a row do not differ significantly according to Tukey's test at 5% probability.
Abbreviations: ns, not significant; SOC, soil organic carbon.

inherently rich in carbon and contributes to creating a favorable environment for microbial activity and root development [29, 33]. In addition to improving organic matter content, FCB application also had a marked influence on soil nutrient dynamics.

In general, FCB application enhanced nutrient availability in the soil, with significantly higher concentrations of P, Ca, Mg, Fe, and Mn observed in FCB-amended treatments compared to the control (Table 3). This suggests that FCB can serve as a nutrient source for plants. However, the results also showed that biochar had no significant effect on the availability of copper and zinc. For Cu, no significant differences were observed in beetroot, and in bell pepper, biochar actually reduced Cu availability. Regarding Zn, no significant changes were observed in bell pepper. These findings indicate that the effect of FCB may vary depending on the specific nutrient [14, 34].

3.3 | Nutrient Concentrations in the Aerial Parts of Vegetables

Macronutrients and micronutrients were evaluated, and their concentrations in plant tissues were compared between the control and FCB-treated conditions. Each element exhibited a distinct pattern, with variations among the vegetable species studied. For instance, the application of FCB significantly increased P concentrations in the aerial parts of all vegetables (Figure 2a). This increase was most pronounced in beetroot, suggesting that FCB application may have enhanced P availability in the soil, either through direct P release from the biochar itself [14] or via changes in soil chemistry. One such change is the increase in soil pH, which reduces P fixation by iron and aluminum oxides, thus improving its availability to plants [14, 32, 34, 35].

Calcium concentrations showed a consistent response (Figure 2b), with a significant increase in plant tissues under the FCB treatment. Biochar contributes directly to Ca supply and also increases soil pH, which enhances Ca availability [32, 34, 35]. Although biochar can increase Mg availability in the soil, its effect on plant uptake varies. A significant increase in Mg concentration was observed in beetroot and bell pepper, whereas Swiss chard and okra showed no statistically significant differences (Figure 2c). This variability may be influenced by other cations such as Ca and K, which compete for the same root absorption sites. Species-specific traits may also play a role in nutrient uptake behavior [29, 31, 34]. These variations may stem from differences in root exudation patterns, which can influence metal solubility and availability in the rhizosphere [36]. Additionally, plant species differ in the expression and regulation of specific transporter proteins involved in the uptake and translocation of micronutrients, such as Fe, Mn, Cu, and Zn [37].

The impact of FCB on Fe concentrations varied among the crops: A significant decrease was observed in okra, whereas significant increases occurred in Swiss chard and beetroot. No significant change was detected in bell pepper (Figure 2d). The reduction in Fe levels in okra may be attributed to biomass dilution, as the plant produces more biomass, the concentration of certain elements may decrease if their uptake does not keep pace. In contrast, the increases in Swiss chard and beetroot suggest that FCB may have facilitated Fe mobilization or created favorable conditions for its uptake. Biochar may release Fe directly or enhance its availability through mechanisms such as pH modification and stimulation of microbial activity [9, 31].

For Mn, an increase in concentration was observed only in Swiss chard following FCB application, whereas the other vegetable species showed a significant reduction (Figure 2e). The increase in soil pH promoted by FCB generally reduces Mn solubility, making it less available to most plants [10, 14]. However, Swiss chard likely has a higher affinity for Mn, either due to a greater physiological requirement for this micronutrient or through specific uptake strategies, such as the presence of Mn transporters in the roots or the release of root exudates [2].

Copper concentrations also varied across species (Figure 2f), with significant reductions observed in Swiss chard and okra, an increase in beetroot, and no significant change in bell pepper. These differences are most likely explained by species-specific physiological traits influencing Cu uptake efficiency [10, 14]. Such variability was particularly evident for micronutrients like Mn and Cu, whose availability and plant uptake are not only influenced by soil chemistry but also by species-specific physiological traits. It is well known that species differ in the expression of specific transporter proteins involved in the uptake and translocation of micronutrients, such as Cu [37].

Zinc concentrations were negatively affected by FCB (Figure 2g), with significant reductions observed in all vegetable species. Biochar may immobilize Zn through several mechanisms, including surface adsorption, complexation with functional groups, and precipitation into less soluble forms. These processes reduce Zn availability in the soil and, consequently, its uptake and accumulation in plant tissues [10, 16, 38]. Although FCB reduced Zn availability in the soil, plant tissue concentrations remained within or near adequate levels, indicating no nutritional deficiency. However, in Zn-deficient soils or for Zn-demanding crops, such reductions could be problematic.

3.4 | Dry Matter Production in Vegetables

Beyond influencing nutrient dynamics and metal availability, the application of FCB also had a pronounced effect on plant growth parameters, particularly biomass accumulation. FCB application significantly affected shoot dry matter (SDM) and root dry matter (RDM) production in vegetables grown in Cd-contaminated soil (Figure 3). A general trend of increased SDM and RDM was observed following the application of FCB. Swiss chard and

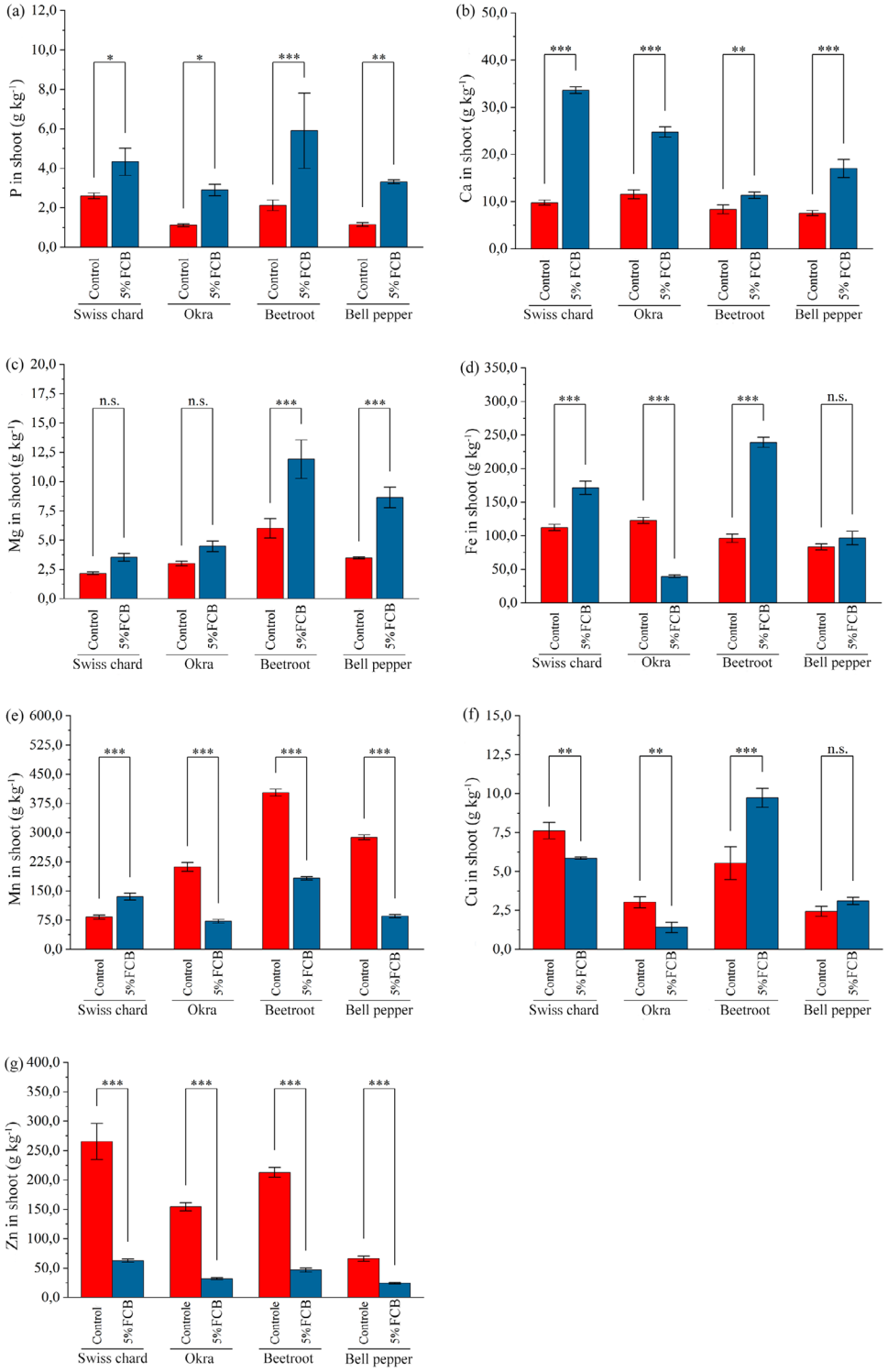


FIGURE 2 | Mean values (±standard deviation) of nutrient concentrations (a) phosphorus; (b) calcium; (c) magnesium; (d) iron; (e) manganese; (f) copper; (g) zinc in the aerial parts of vegetables grown in Cd-contaminated soil treated with 5% filter cake biochar (FCB). ns: not significant, *: significant at 5% probability, **: significant at 1% probability, ***: significant at 0.1% probability, according to Tukey's test.

beetroot showed no statistically significant differences in RDM. Despite this variability among species, one crop in particular demonstrated a notably strong response to FCB addition.

The most notable response was observed in okra, which exhibited a strong positive reaction to FCB application (Figure 3). This enhanced growth is likely attributable to improvements in soil fertility [31, 32, 35, 39], reduction in Cd toxicity [10, 40], and increased soil organic matter [14, 41, 42]. Although okra showed the most pronounced response, these FCB-induced changes are also beneficial to the growth and development of the other vegetable species evaluated in this study.

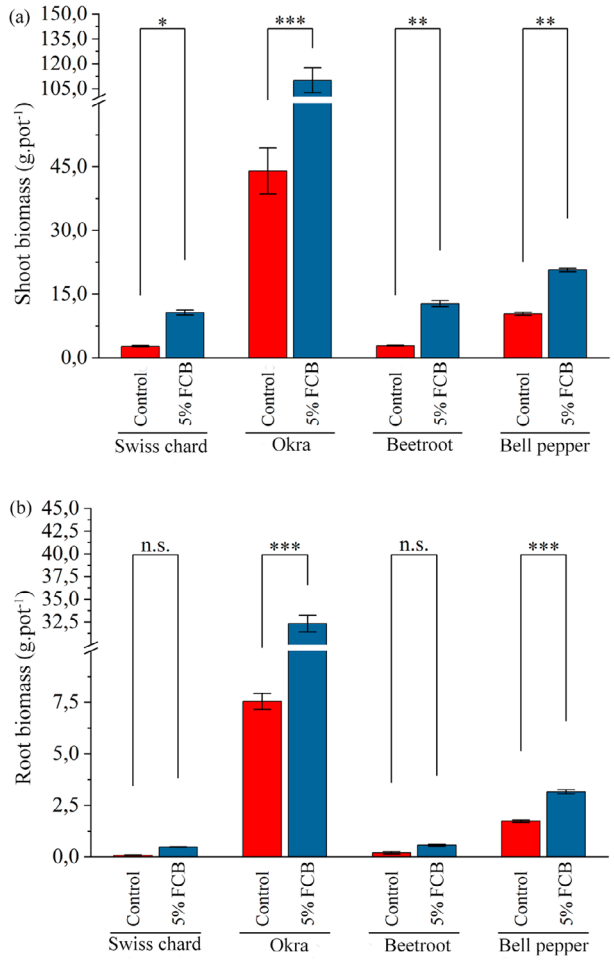


FIGURE 3 | Mean values (±standard deviation) of shoot dry matter (SDM) (a) and root dry matter (RDM) (b) of vegetables grown in Cd-contaminated soil treated with 5% filter cake biochar (FCB). *: significant at 5% probability, **: significant at 1% probability, ***: significant at 0.1% probability, according to Tukey's test. ns, not significant.

3.5 | Pearson Correlations

To evaluate significant correlations among soil and plant variables, and the relationships between them, Pearson correlation matrices ($p < 0.05$) were generated. Most variables showed positive correlations, with particularly strong relationships observed among pH, SOC, soil P, soil Ca, soil Mg, soil Fe, and soil Mn (Figure 4a). For these attributes, correlation coefficients were consistently above 0.70. Such values, approaching 1, indicate strong positive correlations among these soil characteristics.

It is important to note, however, that a positive correlation does not necessarily imply a direct cause-and-effect relationship [43]. For instance, the availability of micronutrients, such as Fe and Mn, typically decreases with rising pH. Yet, in this case, a positive correlation between them was observed, suggesting that other soil-related factors may have contributed to their simultaneous increase. These factors could include the complexation of Fe and Mn with dissolved organic compounds derived from biochar, which can enhance their solubility and mobility even under higher pH conditions. Additionally, biochar amendments can influence microbial community composition and activity, particularly by stimulating siderophore-producing microbes that mobilize Fe and Mn [44]. Redox changes induced by biochar, or shifts in soil aeration and moisture, may also promote the reduction and release of Fe^{2+} and Mn^{2+} from oxide minerals, thereby counteracting the expected decline in availability at elevated pH [45].

Soil Cd concentrations showed a negative correlation with all evaluated soil attributes, with correlation coefficients below −0.75 for pH, SOC, soil P, Ca, Mg, Fe, and Mn. This relationship is expected, as a higher soil pH can reduce Cd availability [9, 46], SOC can complex Cd ions [47, 48], and a higher CEC may indirectly contribute to Cd immobilization [49, 50]. For elemental concentrations in plant tissues, correlations showed less evidence of linearity. This variability can be attributed to species-specific biological characteristics and nutritional demands, which result in different affinities for nutrient uptake.

Notably, SDM and RDM also exhibited negative correlations with Cd and cationic micronutrients in plant tissues. However, it is unlikely that reduced biomass was directly caused by these micronutrients, as they are essential for plant metabolism. Instead, these correlations likely reflect the concurrent variation of these elements with FCB application, due to their chemical similarities with Cd. For instance, Fe, Mn, Zn, and Cu are divalent cations like Cd^{2+}, which may lead to similar chemical behavior and potential competition for uptake sites in plants.

Cd, with its high mobility and ability to utilize nutrient transport pathways, such as the Mn transporter OsNramp5, can be absorbed and translocated via the xylem to all plant tissues [4, 9, 17]. Once distributed, Cd can exert toxic effects, causing structural and physiological damage, such as reduced root and shoot growth [2, 51], ionic imbalances that impair nutrient uptake and transport (e.g., Ca and K) [17, 52], damage to the photosynthetic apparatus [17, 53, 54], and disruptions to cellular functions [17], ultimately resulting in biomass reduction. In this context, understanding how soil properties influence nutrient availability and plant uptake is essential, particularly under Cd stress conditions.

By integrating soil and plant data into a correlation matrix, the influence of soil attributes on plant nutrient levels becomes more evident (Figure 4c). Strong positive correlations were observed between soil fertility parameters (pH, SOC, soil P, Ca, Mg, Fe, and Mn) and nutrient concentrations in plant tissues. This indicates that improved soil nutritional conditions, particularly due to biochar application, favor nutrient uptake and accumulation in plants [31, 34, 41, 55].

Soil nutrient concentrations were also negatively correlated with Cd concentrations in plant tissues, and soil Cd was negatively correlated with plant nutrients as well as SDM and RDM (Figure 4c). These findings suggest complex interactions between nutrients and Cd, in which adequate nutrient availability may mitigate Cd toxicity and uptake [9, 34, 56]. Furthermore, sufficient nutrient concentrations may compete with Cd for root uptake sites, reducing Cd accumulation in plant tissues [57, 58]. In addition, biochar contributes to Cd immobilization in soil while simultaneously supplying essential nutrients.

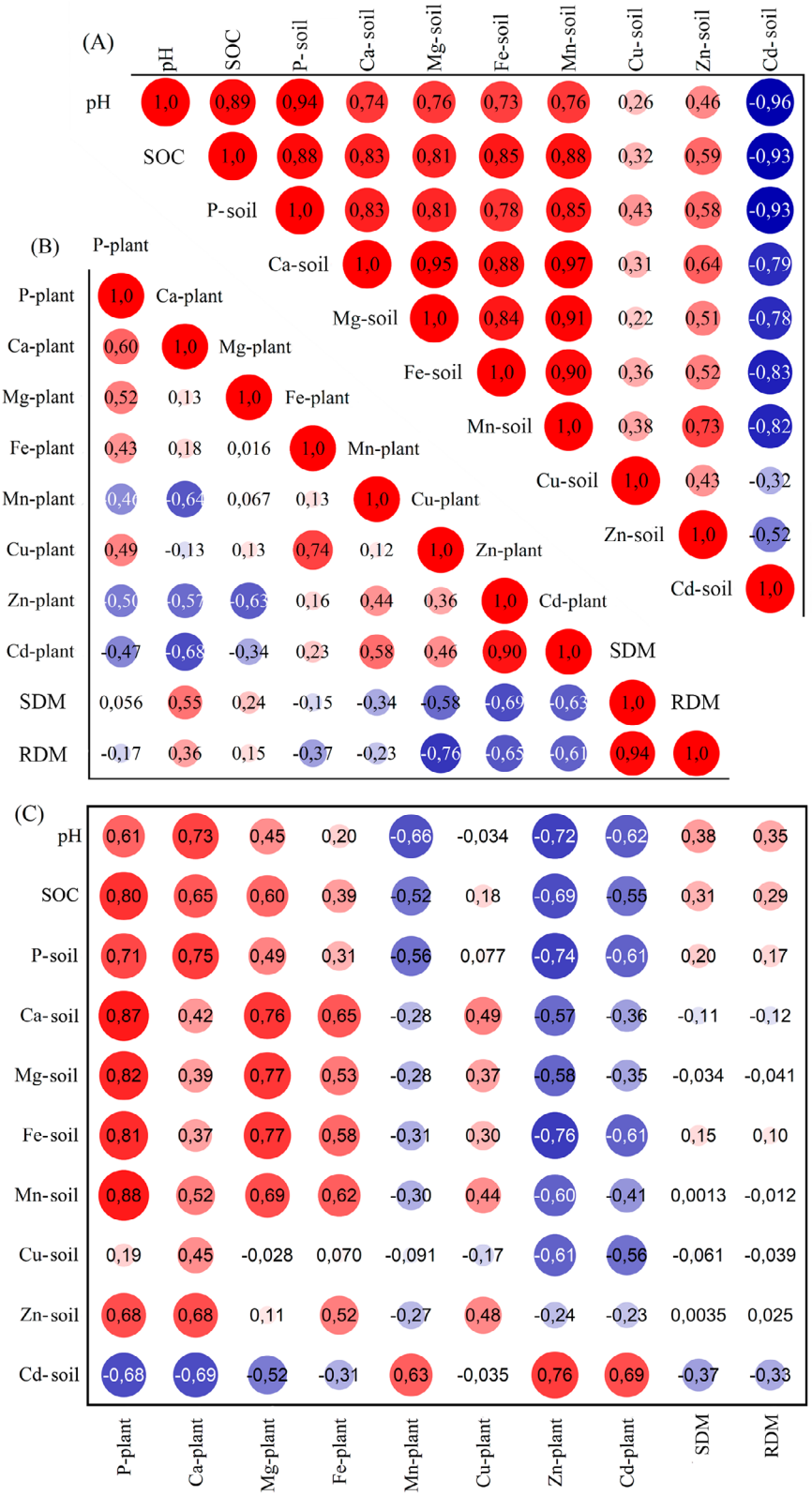


FIGURE 4 | Pearson linear correlation matrix ($p < 0.05$) for: (a) soil variables, (b) variables measured in the aerial parts of vegetables, and (c) correlations between soil and plant variables. All vegetables were cultivated in Cd-contaminated soil treated with 5% filter cake biochar (FCB). Cd, cadmium; RDM, root dry matter; SDM, shoot dry matter.

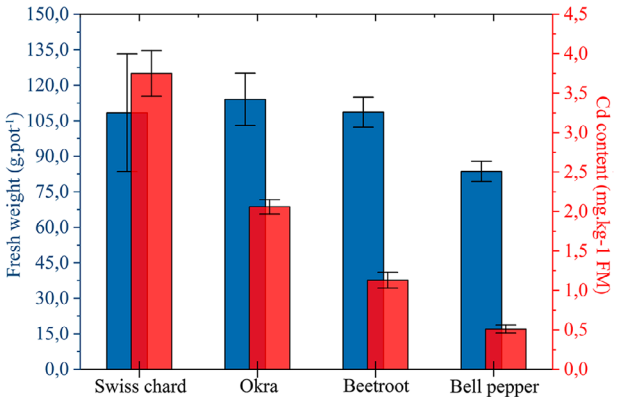


FIGURE 5 | Mean values (±standard deviation) of fresh biomass and cadmium concentrations in the edible tissues of vegetables grown in Cd-contaminated soil treated with 5% filter cake biochar (FCB). Cd, cadmium.

Taken together, these results highlight the role of biochar as a crucial "link" between soil quality, nutrient dynamics, and plant performance. FCB directly improved key soil properties, including organic matter content, pH, and the availability of nutrients, which were positively correlated with plant growth and yield. At the same time, it indirectly enhanced plant health by reducing Cd availability in the soil, thereby limiting Cd uptake and mitigating its phytotoxic effects. This dual function underscores the integrative role of biochar in simultaneously enhancing fertility and minimizing environmental risks in contaminated soils.

3.6 | Cd Concentrations in the Edible Parts of Vegetables

The improvements in soil fertility and plant nutrition not only supported overall growth but were also critical for enabling the development of edible plant structures under Cd-contaminated conditions. Vegetables grown in Cd-contaminated soil without FCB application were exposed to such toxic levels of Cd that they did not reach physiological maturity and thus did not produce edible structures. In contrast, plants treated with FCB were able to develop edible parts, allowing the assessment of Cd accumulation in these tissues (Figure 5).

Once again, Cd accumulation varied according to species. Biomass production in the edible parts was comparable across species, with bell pepper exhibiting the lowest values (Figure 5). Cd concentrations followed a similar trend, with bell pepper accumulating the least Cd, whereas Swiss chard accumulated the highest concentrations. These differences can be attributed to species-specific traits such as root system architecture, affinity for Cd transport mechanisms, and the ability to exclude or sequester Cd in safer compartments within plant tissues.

When comparing the fresh biomass yield of edible parts with their Cd concentrations, some species showed a greater "gap" between these two attributes, indicating potentially more efficient mechanisms of Cd exclusion or compartmentalization into nonedible tissues. These findings further reinforce the role of biochar as an effective strategy for mitigating Cd-induced damage in vegetable crops.

4 | Conclusions

The application of 5% FCB proved effective in remediating Cd-contaminated soil, reducing Cd availability and plant uptake to safe levels. In addition to immobilizing Cd, FCB improved soil fertility by increasing pH, organic carbon, and the availability of nutrients. As a result, only plants grown with FCB reached physiological maturity and produced edible tissues, demonstrating the amendment's ability to mitigate phytotoxicity and restore crop productivity. Species-specific responses in Cd uptake and nutrient accumulation were observed, suggesting differences in physiological traits such as root exudation and metal transporter activity.

These findings highlight the potential of FCB as a sustainable strategy for enhancing food safety and agricultural resilience in tropical regions. However, the study was conducted under greenhouse conditions with a single soil type and one application rate, which may limit extrapolation. Future research should include long-term field trials, different biochar doses, a broader range of crops, and deeper investigation into the mechanisms of Cd tolerance and the potential health risks of residual Cd in edible parts.

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Disclosure

The founding sponsors had no role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, and in the decision to publish the results.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data are available on request from the authors.

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