EFFECT OF QUAIL LITTER BIOCHAR ON PRODUCTIVITY OF FOUR NEW PHYSIC NUT VARIETIES PLANTED IN CADMIUM-CONTAMINATED SOIL

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Biochar can improve soil structure and water retention, enhance nutrient availability and retention, ameliorate acidity, and reduce heavy metal toxicity to plant roots. In this study, a basin experiment was conducted to investigate the effects of quail litter biochar (QLB) on the availability of Cd to physic nut (*Jatropha curcas* L.) plants. QLB was applied to the soil in which four new physic nut varieties (Takfa, Doi Saket, Lao, and Rayong) in factorial combinations at four levels (0, 5, 10, and 15 g kg^{-1} soil) to soil that contained 60.8 mg Cd kg^{-1}. After transplanting plant height and canopy radius were measured every 2-mo and the number of leaves and branches at 6-mo, while yield components and Cd residues were measured at 8-mo intervals. The contaminated soil was analyzed for chemical characteristics, nutrients, and Cd residue after the plant harvest. The addition of QLB to soil caused a significant increase in the soil's growth potential and physic nut yield components (P < 0.05), a significant decrease in the Cd residue in the plant (P < 0.05), and a significant increase in the chemical characteristics, nutrients, and Cd residue in soil (P < 0.05). In conclusion, QLB application can significantly decrease the bioavailability of Cd to physic nut plants, increase plant growth potential and yield, and has potential to remediate Cd-contaminated soil. However, QLB levels higher than 15 g kg^{-1} soil mixture were not advisable because QLB is alkaline in nature, and this can affect soil pH.

Key words: Adsorption, heavy metal, phytoremediation, plant production, pyrolysis, soil amendment.

Cadmium (Cd) is a toxic heavy metal that is an environmental concern (Mahler *et al*., 1981). There are many sources of environmental Cd pollution, including fuel combustion, industrial sludges, phosphate fertilizers, and mine tailings (Unhalekhana and Kositanont, 2008). Cd can be absorbed by the human body through respiration and consumption, and Cd then accumulates in the liver and kidney, causing acute and chronic symptoms such as nausea, abdominal pain, diarrhea, kidney dysfunction, and osteomalacia (soft bones) (Simmons *et al*., 2005). The first and most important case study occurred in the Jinzu river basin, Toyama Prefecture, Japan, in 1950. Private mines had released contaminated wastewater into the river. The water, used by a local community and used to irrigate paddy fields, caused Itai-itai disease, which leads to kidney damage, and more than 100 lives were lost. Since then, studies have found that the Cd concentration around that riverbank is 4.85 mg kg^{-1} soil or approximately 14 times that of unaffected soil (0.34 mg kg^{-1} soil) (Unhalekhana and Kositanont, 2008).

In the Huay Maetao watershed, Mae Sot District, Tak Province, Thailand, Cd residues were found in the environment and in products such as rice, aquatic animals, and drinking water because of nearby mineral extraction activities (Wongsanoon, 2005). These activities included drilling, material transfer, and the removal of mine tailings and drainages (Chanthachot *et al*., 2005). Simmons *et al*. (2005) studied the Cd concentration in 154 soil samples collected in the Huay Maetao area and found Cd levels in rice field soils of 3.40-284 mg kg^{-1} soil, 94 times the European Economic Community's maximum permissible concentration in soil (3 mg kg^{-1} soil). This level of Cd residue has affected the health, livelihoods, and way of life of the farmers living in the area because their production is considered unfit for consumption (Unhalekhana and Kositanont, 2008). To address this problem, one promising approach for restricting Cd contamination in the soil and reducing Cd residues in agricultural products is through adsorption to biochar.

Biochar is a product of thermal decomposition of biomass produced by a process known as pyrolysis (heating in the absence of oxygen) (Chen *et al*., 2010). The microscopic physical structure of biochar is the key to its success in reducing heavy metal contamination (Suppadit,

2009). Hossain *et al*. (2010) reported that biochar can induce an increase the heavy metal fraction of soil and decrease heavy metal uptake in soil. Biochar application reduced the extractability of heavy metals such as Cd from the soil. This significant change in the extractability and in the metal sequential fractions indicated that the available exchangeable form of heavy metals in soil can be transformed into an unexchangeable form (Qiu and Guo, 2010). A separate environmental issue in this area is the disposal of litter from quail farms. The litter can be a source of pathogens, and it can produce poisonous gases during fermentation (Suppadit, 2009). To address both of these issues, using pyrolysis to convert animal waste such as quail litter into biochar could reduce the environmental pollution from both of these sources.

Another significant problem in Thailand is a lack of energy; oil imports amount to more than US$2.86 billion each year (Suppadit, 2003). Plants that can be used for renewable energy or biodiesel that can also be grown in highly Cd-contaminated areas could be an alternative solution to these problems. Physic nut (*Jatropha curcas* L.) is an alternative cash crop that can generate income for the grower. It can be used in oil production because its oil content is 34% and the extraction process is not complicated. The oil obtained can be used directly in an engine without mixing with fuel oil or going through a biodiesel production process. This results in reduced processing costs. Like diesel, physic nut is a highly efficient fuel (Thummaprasit, 2005). The physic nut grows rapidly and produces yields 8-mo after seeding. The grower does not need to use extensive technology to grow it, and it is not part of the food chain (Cock *et al*., 2009; Jaime and Salazar, 2010). In addition, physic nut plants can be used to remove Cd from soil as a phytoremediation method (Mangkoedihardjo and Surahmaida, 2008).

Based on these reasons, the objectives of the present study were to investigate the effect of quail litter biochar (QLB) on soil quality and on the growth, productivity and safety of physic nut plants planted in a rice field soil in the Huay Maetao area, which has a high level of Cd contamination.

MATERIALS AND METHODS

Experimental location and soil collection
The experiment was conducted in the Mae Sot District, Tak Province, Thailand from May 2010 to May 2011. The experiment was performed under natural light and temperatures of 22.5 ± 4 °C at night and 32.5 ± 3.2 °C during day in an open area that measured 20 × 20 m (400 m²). Corrugated iron and blue netting were used as border around the experimental area. The concrete basins in which the physic nut plants were planted were 100 cm in diameter (7857 cm²) × 30 cm high.

Approximately 10 t of soil were collected and mixed from 15 sites within the Huay Maetao area (170 km²).

The soil was classified as part of the Tha Yang soil series (Loamy-skeletal, siliceous, isohyperthermic Kanhaplic Haplustults) (Land Development Department, 2011). This highly Cd-contaminated soil (> 60 mg Cd kg⁻¹ soil) was chosen to determine the effect of QLB treatments on physic nut growth and production. A composite sample of the upper 10 cm of soil was collected and then passed through a 6-mm sieve before mixing, analyzing, and planting according to the methods described by Hossain *et al*. (2010). The chemical characteristics, nutrients, and Cd levels in the soil before the experiment are presented in Table 1.

Biochar production
The biochar used in this study was produced from quail litter. Quail litter was randomly chosen from farms located in Singburi Province, Thailand. QLB was produced using a 500 °C pyrolysis temperature as recommended by Lehmann (2007). The quail litter was packed into a ceramic container, covered with a lid and combusted in a muffle furnace (K-SF05, Humanlab, K&K Scientific Supplier, Seoul, South Korea) at 500 °C for 5 h to generate biochar according to the methods of Uzoma *et al*. (2011). After pyrolysis, the QLB was ground through a 1 mm sieve to ensure the biochar would have the same particle size as the soil used in the experiment. The chemical characteristics, nutrients, and Cd levels in the QLB are presented in Table 1.

Experimental design
Physic nut plants were collected from a local agricultural agency and were bred by the Chiang Mai Field Crops Research Center in January 2003. The physic nut variety and the quantity of the QLB were assessed in a 4 × 4 factorial arrangement with four replicates in a completely randomized design (Johnson and Bhattacharyya, 2001).

Table 1. Chemical characteristics of soil and quail litter biochar (QLB) used in a basin experiment.

Characteristics	Soil	QLB
EC, dS m⁻¹	0.140	2.20
pH	6.90	9.10
Exchangeable cations		
CEC, cmol kg⁻¹	0.980	6.35
K, cmol kg⁻¹	0.230	0.280
Ca, cmol kg⁻¹	0.455	2.34
Mg, cmol kg⁻¹	0.192	1.52
Elements		
C, mg kg⁻¹	1 310	32 800
Total N, mg kg⁻¹	208	1 620
C/N ratio	6.30	20.2
P, mg kg⁻¹	604	9 620
K, mg kg⁻¹	723	6 750
Ca, mg kg⁻¹	1 048	10 050
Mg, mg kg⁻¹	334	1 020
Fe, mg kg⁻¹	4.36	910
Zn, mg kg⁻¹	0.460	182
Cu, mg kg⁻¹	0.910	143
Mn, mg kg⁻¹	13.9	342
Heavy metal		
Cd, mg kg⁻¹	60.8	14.8

EC: electrical conductivity; CEC: cation-exchange capacity.

The first factor was the physic nut varieties Takfa (var. Tak.), Doi Saket (var. Doi), Lao (var. Lao), and Rayong (var. Ray.), and the second factor as the QLB levels at 0 (QLB0), 5 (QLB5), 10 (QLB10), and 15 (QLB15) g kg^{-1} soil. The amount of biochar applied to Cd-contaminated soil was based on previous investigations by Namgay *et al*. (2010). Each basin received 150 kg of air-dried soil, which was then mixed with the various QLB treatments.

Planting and data collection

Physic nut seeds of each variety were planted in individual plastic pots. Three-month-old seedlings were transplanted into the trial concrete basin, with 1 plant basin^{-1}. These were watered every week and weeded by hand. An aqueous solution of tobacco leaves was used for insect control. Soil temperature, moisture, and pH were measured every week, plant height and canopy every 2-mo, and number of leaves and branches at 6-mo after transplanting. The yield components included the number of fruits per plant, the fresh and dry fruits weights of each plant, the fresh and dry fruit weight per fruit, the number of seeds per fruit, and the weight of 100 dry seeds and were measured at 8-mo after transplanting. The oil at harvest was obtained using a screw press.

Laboratory analyses

At the end of the basin experiment, the plant and its seeds and oil, the QLB, and the soil samples were sent to laboratories at the Chiang Mai Field Crops Research Center and Kasetsart University. The soil from each basin was air-dried at 36 °C to constant weight and passed through a 4-mm sieve to separate out the plant debris. The plants and seeds were oven-dried at 70 °C to constant weight before weighing to determine the DM, oil, and Cd content. The Cd residue in plant component tissues was measured using direct aspiration with an atomic absorption spectrophotometer (AAS; Analytik Jena-NVAA 300, Analytica, Jena, Germany) according to the procedures of Tessier *et al*. (1979). Cd and nutrients in the QLB and soil were measured using an inductively coupled plasma emission spectrophotometer (ICPES; ACTIVA-M, Horiba Jobin Yvon, Tramoyes, France) according to the procedures of AOAC (1970; 1980). QLB and soil chemical characteristics were analyzed for EC (electrical conductivity meter; Amber Science 4083, Amber Science, Oregon, USA), pH (pH meter; Sension 156, HACH, Colorado, USA), moisture (Tensiometer; BP100, KRUSS, Hamburg, Germany), and organic matter (OM) (Walkley-Black method), based on procedures from the Land Development Department (2004) manual. CEC was estimated using an NH$_4^+$-replacement method according to procedures of Schollenberger and Simon (1945), and leachates were analyzed for exchangeable cations K, Ca, and Mg according to procedures described by Uzoma *et al*. (2011).

Statistical analyses

Data were analyzed using ANOVA. When significant differences were found, the least significant difference (LSD) test of the Statistical Analysis System (SAS version 6.12) was used to test for interactions and differences among the treatment means at a significance level of $P < 0.05$ (SAS Institute, 1996).

RESULTS AND DISCUSSION

Growth potential and yields

There were no interactions between the physic nut variety and the QLB level factors in terms of the total growth potential or any of the yield components. Plant height (Figure 1a), canopy radius (Figure 1b), number of leaves (Figure 1c), and number of branches (Figure 1d) at the initial stage of the experiment were not significantly different among the four varieties (P > 0.05). Measurements taken 2, 4, 6, and 8-mo after transplanting showed that there were still no statistically significant differences in plant height or canopy among the four varieties (P > 0.05). Similar to the measurements taken at 6-mo, there were no differences in the number of leaves or the number of branches among four varieties (P > 0.05). Yield components were assessed in terms of the number of fruits per plant, fresh fruit weight per plant, dry fruit weight per plant, fresh fruit weight per fruit, dry fruit weight per fruit, number of seeds per fruit, dry weight of 100 seeds, and percentage of oil per seed weight (Table 2). At the end of the 8-mo experiment, there were no significant differences among physic nut varieties ($P > 0.05$). However, all varieties of physic nut plants planted in Cd-contaminated soil without QLB showed a lower in growth potential and lower yield components than in the other treatments (P < 0.05), likely because 60.8 mg Cd kg^{-1} soil has an adverse effect on plants by affecting metabolic processes, photosynthesis, and respiration (Mahler *et al*., 1981), leading to slower growth than in physic nut plants planted in normal soil (Suppadit *et al*., 2008). Francis (1994) reported that Cd at 1-10 mg kg^{-1} could affect the growth potential of lettuce. Similarly, Sanoh (2005) found that growth potential of vetiver grass, sunflower, and rice decreased with increasing Cd levels, stunting their growth. Chehregani and Behrouz (2007) and Mangkoedihardjo and Surahmaida (2008) reported that physic nut plants grew normally when the level of Cd residue was < 50 mg kg^{-1}.

There was a significant ($P < 0.05$) increase in the growth potential and yields of the all physic nut varieties with increasing soil QLB level. The application of QLB in Cd-contaminated soil increased the growth and yield of physic nut plants compared to the non-QLB treatments, likely because QLB was both a soil fertilizer and a soil amendment. The QLB increased nutrient availability, particularly of N (Schmidt and Noack, 2000). The QLB was not easily degraded by soil microbes, which favored
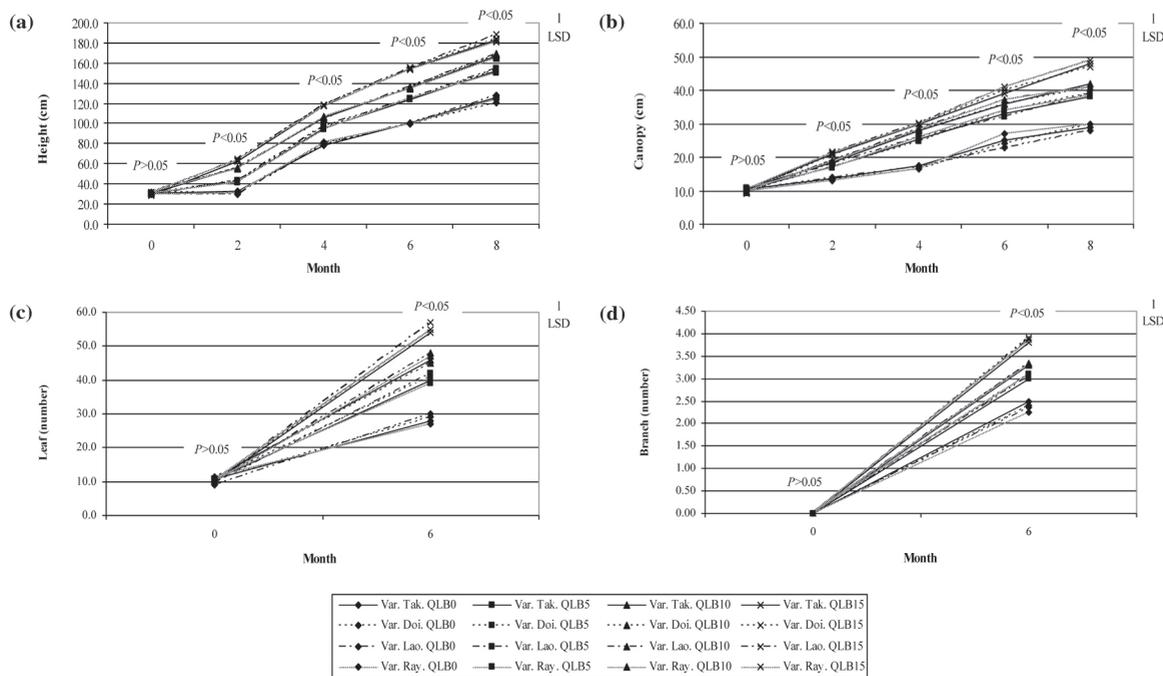
Figure 1. Plant height (a), canopy (radius) (b), number of leaves (c), and number of branches (d) of four physic nut varieties planted in Cd-contaminated soil treated with quail litter biochar (QLB) at various levels. Vertical lines represent LSD at $P = 0.05$.

the incorporation of this material into the soils (Glaser *et al.*, 2002). Because QLB is a porous material with a high surface area (Liang *et al.*, 2006), it could be affected by soil moisture and nutrient dynamics (Uzoma *et al.*, 2011). These results imply that the addition of QLB to soil allowed percolating soil moisture more residence time within the root zone, thereby making the soil moisture and nutrients more available to growing physic nut and eventually improving crop productivity (Steinbeiss *et al.*, 2009). In addition, the increase in physic nut growth and yield was mainly due to the improvement in soil CEC and the increased nutrient content of the soil (Hossain *et al.*, 2010). However, these results should be interpreted with caution; the soil pH increased with increasing QLB mixture because QLB is alkaline (Suppadit, 2009). The optimum soil pH for physic nut production is 6.5-7.5 (Suppadit *et al.*, 2008).

Cd residue in plant

There was no interaction between physic nut variety and QLB level in terms of the amount of Cd residue in plants. There were no differences in the amount of Cd residues in the stem, root, leaves, seed, oil, or seed meal ($P > 0.05$) among physic nut varieties (Table 2). This finding indicates that all physic nut varieties were able to absorb Cd from the soil at nearly the same rate. The Cd levels in tissues of plants grown in Cd-contaminated soil without QLB treatments were higher than legal limits of 0.1-2.0 mg kg^{-1} (Pollution Control Department, 2006), except for seed meal. Phytoextraction, through convection and diffusion,

leads to the accumulation of Cd in the plants (Crowley *et al.*, 1991). Cd ions dissolved in water move from soil solids at the rhizosphere to the root (Panichasakpatana, 1996). The water is absorbed by the root to replace water used in respiration (Romheld and Marschner, 1986). Cd accumulates in roots more than in stems and leaves because roots have more opportunities to come into contact with Cd and have longer Cd accumulation times than stems or leaves (Suppadit *et al.*, 2008). These results are in agreement with a study by Giesy *et al.* (1981), who found the highest Cd levels in root tissues, followed by stems and then the leaves of mangrove plants. Meanwhile, all varieties of physic nut had a significantly ($P < 0.05$) lower level of Cd residue in all plant tissues when there was a higher level of QLB in the soil. The results clearly show the ability of QLB to immobilize a mixture of Cd in soil. In fact, the bio-available fraction of heavy metals is reduced in the presence of biochar (Uchimiya *et al.*, 2010). The strong binding of Cd to the surface functional group of biochar makes it less available to the plants (Namgay *et al.*, 2010). Hossain *et al.* (2010) reported that biochar can increase the heavy metal fraction of soils and decrease the uptake of heavy metals. Biochar application reduces the extractability of heavy metals in soil and causes significant changes in the extractability and metal sequential fractions, indicating that the available form of heavy metals in soil can be transformed into unexchangeable forms (Qiu and Guo, 2010). Cao and Ma (2004) found that addition of biochar decreased Cd accumulation in carrots and lettuce. Therefore, QLB can

Table 2. Yield components and Cd residue of four varieties of physic nut plants grown with four levels of quail litter biochar (QLB) in soil.

Items	Var. Tak.				Var. Doi				Var. Lao				Var. Ray.				CV (%)
	QLB0	QLB5	QLB10	QLB15	QLB0	QLB5	QLB10	QLB15	QLB0	QLB5	QLB10	QLB15	QLB0	QLB5	QLB10	QLB15	
Yield components																	
Fruits/plant	6.88d	7.95c	8.08b	8.20a	6.86d	7.94c	8.10b	8.22a	6.90d	7.96c	8.09b	8.23a	6.85d	7.92c	8.01b	8.19a	10.5
Fresh fruit weight/plant, g	130d	155c	162b	176a	127d	157c	163b	179a	129d	158c	163b	178a	126d	152c	161b	175a	12.3
Dry fruit weight/plant, g	30.9d	41.2c	43.1b	44.0a	30.0d	40.9c	42.9b	43.8a	29.9d	41.3c	43.0b	43.7a	30.3d	41.0c	42.8b	43.8a	9.60
Fresh fruit weight/fruit, g	18.9d	19.5c	20.0b	21.5a	18.5d	19.8bc	20.1b	21.8a	18.7d	19.8bc	20.1b	21.6a	18.4d	19.2c	20.1b	21.4a	10.4
Dry fruit weight/fruit, g	4.49d	5.18c	5.33ab	5.36a	4.37d	5.15c	5.30b	5.34ab	4.42d	5.19c	5.32ab	5.33ab	4.42d	5.18c	5.34ab	5.35a	12.8
Number of seeds/fruit	2.88d	3.05c	3.12b	3.15ab	2.90d	3.06c	3.11b	3.16a	2.86d	3.06c	3.10b	3.15ab	2.91d	3.04c	3.12b	3.17a	9.02
Weight of dry 100 seeds, g	30.2d	34.0c	38.5b	40.1a	29.8d	33.9c	38.3b	40.0a	29.5d	33.6c	38.2b	39.8a	30.5d	33.9c	38.4b	40.0a	7.34
Oil/seed weight, %	24.8d	27.6c	29.5b	30.6a	24.5d	27.4c	29.8b	30.5a	24.6d	27.3c	29.4b	30.2a	24.8d	27.5c	29.6b	30.5a	5.62
Cd residue																	
Stem, mg kg⁻¹	6.45a	4.20b	2.99c	1.86b	6.42a	4.18b	2.96c	1.80b	6.46a	4.22b	3.00c	1.87b	6.42a	4.17b	2.96c	1.85b	8.46
Root, mg kg⁻¹	22.50a	15.40b	10.30c	5.20d	22.40a	15.20b	10.10c	5.17d	22.60a	15.60b	10.4c	5.23d	22.20a	15.00b	10.10c	5.18d	9.12
Leaf, mg kg⁻¹	3.20a	2.94b	2.00c	1.36d	3.18a	2.90b	1.99c	1.32d	3.22a	2.97b	2.01c	1.38a	3.19a	2.93b	2.02c	1.34d	6.85
Seed, mg kg⁻¹	2.65a	2.34b	1.88c	1.12d	2.63a	2.30b	1.86c	1.12d	2.66a	2.37b	1.90c	1.14d	2.64a	2.32b	1.87c	1.09d	5.20
Oil, mg kg⁻¹	3.12a	2.67b	1.93c	1.22d	3.11a	2.65b	1.90c	1.20d	3.15a	2.69b	1.94c	1.24d	3.10a	2.63b	1.90c	1.19d	7.44
Seed meal, mg kg⁻¹	1.64a	1.32b	1.11c	0.880d	1.61a	1.31b	1.10c	0.875d	1.65a	1.34b	1.12c	0.892d	1.63a	1.31b	1.10c	0.850d	6.95

Means in the same row with different letters are significantly different at P < 0.05.

significantly affect heavy metal absorption (Uchimiya *et al*., 2010), acting as a barrier against the negative characteristics of heavy metal contamination (Kookana, 2010) and mitigating the adverse influence of heavy metals on plant growth and yield (Chen *et al*., 2010).

Chemical characteristics, nutrients, and Cd residue in soil

There were no interactions between physic nut variety and QLB level factors for total chemical characteristics, nutrients, or amount of Cd residue in soil. Although there were no changes in pH or C/N ratio, Cd-contaminated soil without QLB showed a decrease in EC, exchangeable cations, soil nutrients, and Cd, when compared to the levels in the soil before the experiment (Table 3). This may be because these substances were absorbed by the plants as well as leached by watering and rainfall (Suppadit, 2005). In addition, there were no significant differences (P > 0.05) in the levels of EC, pH, exchangeable cations, soil nutrients, and heavy metal among the four varieties of physic nut. This finding implies that soil nutrients and Cd were absorbed at almost the same rate by each variety. There was a significant (P < 0.05) increase in the EC, pH, exchangeable cations, and soil nutrients of all varieties when there was an increase in the soil QLB level. QLB may have the ability to increase the mineralization of soil organic N upon its incorporation into soil because of its priming effect (Hamer *et al*., 2004) and its high C content (Singh *et al*., 2010). However, increasing the amount of QLB increased the soil C more than the soil N. This was reflected in the significant increase in the C:N ratio with increasing amounts of QLB. After adding QLB, the more optimal C:N ratio promoted mineralization of C compounds by enhancing the growth of microorganisms and releasing the available N. Exchangeable nutrients (K, Ca, and Mg) and cation-exchange capacity (CEC) in post-harvest soils were higher in the treatments in which more QLB was applied. QLB improved the exchangeable cation status and CEC and increased the nutrient availability of the soil (Chan *et al*., 2008). The formation of surface functional groups and adsorption sites on biochar can influence its CEC (Cheng *et al*., 2006; Liang *et al*., 2006). The increase in pH caused by biochar application may also have enhanced the adsorption of Cd to biochar (Namgay *et al*., 2010). The development of carboxylic-C and aromatic-OH functional groups on biochar surfaces during their oxidation (Liang *et al*., 2006) could also have increased the CEC of the soil (Cheng *et al*., 2006) and possibly increased the Cd-exchange capacity of the soil (Namgay *et al*., 2010). The adsorption and retention capacity for nutrient ions, such as K, Ca, and Mg released from fertilizer, the maintenance of an adequate water supply and a slow release of nutrients might also have caused these increases (Eshghi *et al*., 2010). Asai *et al*. (2009) also reported an increase in plant productivity after biochar application, and they attributed this increase

Table 3. Chemical characteristics, nutrients, and heavy metal in soil after amendment with quail litter biochar (QLB).

Items	Var. Tak.				Var. Doi				Var. Lao				Var. Ray.				CV (%)
	QLB0	QLB5	QLB10	QLB15	QLB0	QLB5	QLB10	QLB15	QLB0	QLB5	QLB10	QLB15	QLB0	QLB5	QLB10	QLB15	
EC, dS m⁻¹	0.138d	0.220c	0.262b	0.300a	0.135d	0.223c	0.266b	0.298a	0.137d	0.219c	0.260b	0.304a	0.130d	0.221c	0.265b	0.303a	7.78
pH	6.93d	7.00c	7.19b	7.32a	6.95d	7.02c	7.20b	7.35a	6.98d	7.04c	7.26b	7.36a	6.96d	7.08c	7.24b	7.40a	8.25
Exchangeable cations																	
CEC, cmol kg⁻¹	0.978d	1.990c	2.100b	2.230a	0.970d	1.970c	2.060b	2.190a	0.960d	1.890c	2.010b	2.200a	0.975d	1.940c	2.130b	2.250a	9.25
K, cmol kg⁻¹	0.226d	0.254c	0.268b	0.290a	0.222d	0.255c	0.270b	0.289a	0.220d	0.252c	0.265b	0.288a	0.221d	0.252c	0.265b	0.296a	6.88
Ca, cmol kg⁻¹	0.450d	0.470c	0.492b	0.513a	0.446d	0.472c	0.490b	0.515a	0.445d	0.468c	0.486b	0.508a	0.451d	0.462c	0.487b	0.509a	12.1
Mg, cmol kg⁻¹	0.188d	0.276c	0.302b	0.322a	0.184d	0.277c	0.305b	0.329a	0.182d	0.270c	0.300b	0.318a	0.187d	0.277c	0.304b	0.326a	8.23
Elements																	
C, mg kg⁻¹	1289d	1699c	2089b	2489a	1276d	1676c	2076b	2476a	1290d	1690c	2090b	2498a	1282d	1682c	2081b	2482a	10.1
Total N, mg kg⁻¹	197d	230c	248b	263a	196d	233c	252b	270a	199d	235c	256b	267a	196d	228b	240b	266a	13.5
C/N ratio	6.54d	7.39c	8.42b	9.46a	6.51d	7.19c	8.24b	9.17a	6.48d	7.19c	8.16b	9.36a	6.54d	7.38c	8.67b	9.33a	17.2
P, mg kg⁻¹	583d	653c	670b	682a	580d	655c	675b	689a	585d	659c	680b	692a	579d	650c	668b	676a	6.78
K, mg kg⁻¹	695d	772c	813b	826a	692d	776c	819b	840a	690d	770c	811b	825a	688d	770c	818b	830a	8.90
Ca, mg kg⁻¹	990d	1055c	1074b	1088a	981d	1050c	1063b	1078a	987d	1051c	1072b	1080a	984d	1048c	1076b	1092a	9.34
Mg, mg kg⁻¹	301d	772c	810b	822a	299d	768c	814b	828a	296d	768c	808b	816a	303d	776c	812b	827a	10.6
Fe, mg kg⁻¹	4.05d	4.84c	5.54b	6.06a	4.02d	4.93c	5.59b	6.15a	4.03d	4.78c	5.49b	5.99a	4.08d	4.85c	5.58b	6.09a	12.3
Zn, mg kg⁻¹	0.438d	0.660c	0.872b	1.03a	0.433d	0.672c	0.880b	1.05a	0.432d	0.656c	0.865b	1.02a	0.440d	0.665c	0.877b	1.05a	19.8
Cu, mg kg⁻¹	0.850d	1.11c	1.43b	1.90a	0.844d	1.12c	1.46b	1.95a	0.851d	1.09c	1.42b	1.88a	0.853d	1.14c	1.46b	1.99a	17.5
Mn, mg kg⁻¹	13.0d	18.5c	20.4b	23.2a	13.2d	18.6c	20.8b	23.9a	12.7d	18.4c	20.6b	23.0a	12.8d	18.6c	20.8b	23.7a	9.01
Heavy metal																	
Cd, mg kg⁻¹	36.5d	43.8c	47.2b	50.3a	36.0d	44.8c	46.3b	51.4a	36.2d	44.1c	47.0b	50.6a	36.3d	43.9c	47.9b	51.4a	12.6

Means in the same row with different letters are significantly different at P < 0.05.

to the increase in available soil nutrients. Therefore, the increased physic nut growth and yield might be due to the greater availability of nutrients from the soil. At the same time, an increase in the level of remaining Cd in soil was observed and corresponded to an increased level of QLB. QLB is alkaline in nature (Suppadit, 2009) and Cd in more alkaline soil moves slowly and shows less leaching after watering or rainfall (Panichasakpatana, 1996). In addition, QLB can significantly decrease due to the heavy metal absorption by plant (Uchimiya *et al*., 2010).

CONCLUSIONS

These results highlight the potential benefits of QLB application for remediating Cd-contaminated soils, which are widespread in the Huay Maetao watershed. The QLB has a positive effect on soil quality and lays a foundation for the improved growth and yield of the four new physic nut varieties. The addition of QLB allowed the percolating soil moisture to have a longer residence time within the root zone, thereby making soil moisture and nutrients more available to the growing physic nut plants and eventually improving crop productivity. The QLB had the potential to decrease the availability of Cd to physic nut plants. The concentration of Cd in physic nut components decreased with increasing application of QLB to the soil. Therefore, the results from this study can be used to predict the efficiency of QLB application when it is used to remediate Cd-contaminated soil. However, more than 15 g QLB kg⁻¹ soil mixture should not be used because soil pH was raised above the requirements for physic nut plants. There is a need for additional field experiments to evaluate long-term benefits of QLB addition at various application rates including its potential to reduce the bioavailability of toxic trace elements in Cd-contaminated soils.

Efecto del biocarbón de cama de codorniz en la productividad de cuatro variedades nuevas de jatrofa plantadas en suelo contaminado con cadmio. Se ha visto que el biocarbón mejora la estructura del suelo y la retención de agua, mejora la disponibilidad y la retención de nutrientes, controla la acidez y reduce la toxicidad de metales pesados en las raíces de las plantas. En este trabajo se investiga el uso de biocarbón de cama de codorniz (QLB) en la disponibilidad de Cd para la planta de jatrofa (*Jatropha curcas* L.) en un estudio de laboratorio. Se realiza una combinación factorial con

cuatro variedades nuevas de jatrofa (Takfa, Doi Saket, Lao y Rayong) sobre cuatro proporciones de QLB a 0, 5, 10, y 15 g kg⁻¹ añadidos por separado a suelo contaminado con 60,8 mg Cd kg⁻¹. Tras el trasplante se midió la altura de la planta y la cubierta vegetal cada 2 meses, el número de hojas y ramas a los 6 meses y los parámetros de rendimiento así como el residuo de Cd a los 8 meses. A continuación, tras la cosecha de la planta, se analizaron las características químicas, nutrientes y residuo de Cd en el suelo contaminado. El uso de QLB causó un aumento significativo en el potencial de crecimiento y en los parámetros de rendimiento ($P < 0,05$), así como una disminución significativa del residuo de cadmio en las plantas ($P < 0,05$) y una mejora significativa en las características químicas, nivel de nutrientes y residuo de Cd en el suelo ($P < 0,05$). Se concluye que el uso de QLB puede disminuir significativamente la biodisponibilidad de Cd para la jatrofa, incrementar su potencial de crecimiento y rendimiento, y tiene el potencial de remediar el suelo contaminado con Cd. No obstante, no se aconseja el uso de QLB por encima de 15 g kg⁻¹ de suelo. Dado que el QLB es de naturaleza alcalina puede afectar al pH del suelo.

Palabras clave: Adsorción, metales pesados, fitorremediación, producción de plantas, pirólisis, enmienda de suelos.

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