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Paclobutrazol Improved the Reproductive Growth and the Quality of Seed Oil of *Jatropha curcas*

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Abstract *Jatropha curcas* was treated by soil drench paclobutrazol (PBZ) (0, 2, and 3 g m^{-1} of canopy diameter) and foliar spray PBZ (0, 500, 800, and 1,200 ppm). The results showed that PBZ treatments greatly retarded vegetative growth and improved reproductive growth. The lengths of new branches were greatly decreased, whereas the number of fruits per inflorescence, fruit-bearing branches per tree, and total fruit load per tree were increased. Only the 2-g soil drench and the 1,200-ppm foliar PBZ spray significantly increased fruit load. The 2-g soil drench PBZ treatment resulted in a decrease in seed S and Cu contents of *J. curcas*, whereas Mn and B were greatly or moderately increased. A higher dose (3-g soil drench PBZ) reversed the improvement in reproductive growth and alleviated the negative effects on element contents in seeds compared with the 2-g soil drench PBZ. Finally, soil drench PBZ treatments significantly improved seed oil content and oil quality by reducing the oil acid value, increasing stearic acid and oleic acid contents, and reducing palmitic acid and linoleic acid content. The optimum drench dose was below 2 g m^{-1} of canopy diameter. The optimum foliar spray concentration of PBZ was not determined in this study but our results suggest that it is higher than 1,200 ppm.

Keywords Paclobutrazol · *Jatropha curcas* · Growth · Seed oil composition

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Introduction

Jatropha curcas L. is an ideal petrosubstitute because of its high-oil-content seeds, low nutrient requirement, and drought tolerance. Large-scale cultivation of *J. curcas* in sites such as wastelands, degraded lands, and mine-contaminated lands has the potential to meet the increasing demand for oil seed crops without scarifying agricultural land. However, nut production of *J. curcas* is very low. In semiarid areas and cultivated wasteland, Heller (1996) and Tewari (2007) propose an achievable dry seed production of 2–3 tons ha^{-1} $year^{-1}$, which was confirmed by field data from Francis and others (2005). When good sites (good soil and average annual rainfall of 900–1,200 mm) are claimed and/or optimal management practice is used, 5 tons dry seed ha^{-1} $year^{-1}$ can be achieved (Foidl and others 1996; Francis and others 2005; Tewari 2007). Planting *J. curcas* brings no economic benefit due to low nut yield, which would greatly prevent the development of it as an energy crop. Therefore, it is important to increase the nut production of *J. curcas*.

Paclobutrazol (PBZ), a triazole compound, is widely used as a growth retardant for controlling vegetative growth in a wide range of angiosperm species (De Jong and Doyle 1984; Quinlan and Richardson 1984; Sterret 1985; Terri and Millie 2000). It can effectively reduce shoot growth of *Swainsona formosa* when drenched at 10, 20, and 50 mg/pot (Hamid and Williams 1997). Similarly, when *Ficus microcarpa* plants were treated with 5 g PBZ L^{-1}, plant height was reduced to approximately 1/10 that of nontreated plants (Ahmad Nazarudin and others 2003). PBZ retarded plant growth by inhibiting gibberellin biosynthesis or action and by slowing the movement of indole-3-acetic acid (IAA) in shoot tips (Rademacher and others 1984; Graebe 1987). On the other hand, PBZ promoted flowering at certain doses in several woody, perennial, and annual plants such as *Bouvardia humboldtii* Hum and *Bougainvillea glabra* Choisy (Wilkinson and Richards 1987; Karaguzel and Ortacesme 2002), and it also increased the average fruit size and yield of 'Crimson Gold' nectarines as well as the flower bud formation and yield in cherries (Blanco 1988; Kaska and others 1991). When applied to soil, a continuous supply of PBZ is taken up by the roots and translocated acropetally via the xylem. Thus, it is important to maintain the concentration of PBZ above the threshold required for the inhibition of gibberellin biosynthesis (Davis and others 1988) to successfully restrict vegetative growth during the critical periods for fruit set, growth, and maturation, which results in enhanced fruit set, increased fruit size, advanced fruit maturation, and potential improvements in fruit quality (Martin 1989). Arzani and others (2000) reported that PBZ application advanced flowering of 5-year-old vigorous 'Sundrop' apricot trees by 2–4 days, and increased fruit set, final fruit number, and yield efficiency.

In this study, *J. curcas* trees were treated with different doses of PBZ by foliar spray and soil drench. The aims of this study were (1) to analyze the effect of PBZ on growth, flowering, fruit set, and nut yield of *J. curcas*; (2) to evaluate the difference in the effect of different doses of PBZ application on the *J. curcas*; and (3) to explore the method of PBZ application to improve the nut yield of *J. curcas*.

Material and Methods

Experiment Design

Field experiments were carried out in a plantation (105°50′E 25°28′N; elevation 405 m) in Zhenfeng County, Guizhou province, China, with an average annual temperature of 18.5 °C and an average annual rainfall of 1,010 mm. The *J. curcas* trees in our experiments were planted (density: 2 × 2 m) in July 2005 in the plantation with an area of about 1.5 ha. The physicochemical properties of the soil in the plantation are provided in Table 1. Both experiments A and B were carried out in this plantation. Healthy and strong trees free of pests and disease and of uniform height were selected, and the experiments were carried out in a randomized block design with three (experiment A) or four (experiment B) treatments. Each treatment included four replications, and each replication had five individual trees. These treatments were allocated randomly among the shrubs within each of the replications. In experiment A, PBZ [(2RS, 3RS)-1-(4-chlorophenyl)-4,4-dimethyl-2-(1*H*-1, 2,4-triazol-1-il) pentan-3-ol)] (15 % w/w SP, Guoguang Ltd., China), was applied as a soil drench at 0 (control), 2, and 3 g [active ingredient (ai) of 0, 0.3, and 0.45 g, respectively] m^{-1} canopy diameter (CD) of *J. curcas*. The treatments were applied once on 28 March 2009. In experiment B, PBZ was applied as a foliar spray at 0 (control), 500, 800, and 1,200 ppm on 25 April (the first leaf was mature), 10 May, and 25 June 2009, respectively. Before the treatment, 100 g of a K_2SO_4-type NPK compound fertilizer (16N–16P_2O_5–16K_2O) with sulfur (30 %) was applied to each tree as a soil drench to the

Table 1 Physicochemical properties of soil

	pH	Organic content (g kg^{-1})	TN (g/kg)	TP (g kg^{-1})	TK (g kg^{-1})	AHN (mg kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})	AS (mg kg^{-1})	AB (mg kg^{-1})
Upper soil layer (20 cm)	5.65	16.20	1.128	0.311	19.93	70	<0.02	80	13	<0.01
Middle soil layer (20–40 cm)	5.56	13.66	1.006	0.227	20.22	61	<0.02	70	18.5	<0.01
Lower soil layers (40–60 cm)	5.58	13.18	0.918	0.210	24.18	58	<0.02	80	29	<0.01

The soil was sampled from three soil profiles: upper (0–20 cm), middle (20–40 cm), and lower (40–60 cm)

TN total nitrogen, *TP* total phosphorus, *TK* total potassium, *AHN* alkali-hydrolyzable N (nitrogen), *AP* available phosphorus, *AK* available potassium, *AS* available sulfur, *AB* available boron trees subjected to PBZ treatment on 28 March 2009. The mean CD of the shrubs before the start of the experiment was 175 ± 10 cm. PBZ and fertilizer were mixed in 5 L of water per shrub and then was poured uniformly in circular trenches in the soil (about 20 cm wide and 15 cm deep) around the base at a radial distance of 40 cm from it.

Soil Analysis

Before PBZ application, soil samples were taken at random at the experimental sites, air-dried, screened to pass through a 2-mm sieve, and analyzed for organic compound, pH, total and available contents of N, P, and K, and contents of available S and B. All analyses were carried out following the standard procedure described by Chapman and Pratt (1961).

Oil Content, Oil Composition, and Nutrient Element Content of Seed Analysis

Mature seeds were collected from every replication for analysis of oil content, acid value, ester composition, and nutrient elements. In addition, the weight of 50 dried seeds and the length and diameter of each seed were measured. The oil concentration of mature seeds and the acid value of the oil per each treatment were analyzed by methods described by Pant and others (2006) and Kardash and Tur'Yan (2005), respectively. The compositions of the five major fatty acids of the oil (stearic acid, oleic acid, palmitoleic acid, palmitic acid, and linoleic acid) were analyzed using their methyl esters which were prepared by the boron trifluoride-methanol method (Hossain and others 2003). The methyl esters of the fatty acids were isolated by partitioning with *n*-hexane and water. The hexane-soluble material was then concentrated by rotary vacuum evaporator and analyzed by GC/MS.

Seed samples were oven-dried at 70 °C to constant weight before grinding with a Wiley mill to pass through a 0.5-mm sieve. Total N was measured by the micro-Kjeldahl procedure (Bremner 1965). To determine the remaining elements, plant samples were first subjected to wet digestion in an acid mixture of 5:1 concentrated HNO_3 (69 %) and concentrated $HClO_4$ (70 %) (Mehlich 1984). P content was determined by the vanado-molybdate method (Murphy and Riley 1962), and the K concentration was estimated by flame photometry (Heald 1965). The concentrations of Fe, Mn, Cu, S, and B were analyzed with an atomic absorption flame emission spectrophotometer (Shimadzu, Japan) (Pratt 1965).

Vegetative and Reproductive Behavior Traits Measurement

Three healthy and strong trees were chosen from each replication for the measurement of the lengths and basal diameters of the new branches that were developed at 110 days after PBZ treatment, and the three strongest branches on each tree were selected for measurement in July 2009. The number of fruit; the number of female, male, and total flowers in one inflorescence; and the number of fruit and the branches bearing fruit on one tree also were recorded in July 2009. Because foliar spray PBZ treatments resulted in a fruit load much lower than the 2-g PBZ soil drench, the floral and nutrient elements of seed from trees receiving the foliar spray PBZ treatments were not analyzed.

Table 2 Effects of soil drench and foliar spray paclobutrazol on the vegetative and reproductive growth of *Jatropha curcas*

	Soil drench PBZ (g m^{-1} CD)			Foliar spray PBZ (ppm)			
	0	2	3	0	500	800	1,200
BL (cm)	93.3 ± 12.9a	34.6 ± 12.0b***	33.9 ± 8.4b***	68.7 ± 5.6a	54.3 ± 6.8b***	51.6 ± 7.3b***	39.3 ± 8.2c***
BD (cm)	2.15 ± 0.30a	1.88 ± 0.26b**	1.78 ± 0.26b***	1.63 ± 0.11b	1.99 ± 0.19a***	1.97 ± 0.20a***	1.91 ± 0.20a***
Ratio (BD/BL)	0.023 ± 0.002b	0.059 ± 0.016a***	0.054 ± 0.010a***	0.024 ± 0.002c	0.037 ± 0.005b***	0.039 ± 0.007b***	0.05 ± 0.006a***
nff	7.8 ± 1.5c	13.2 ± 2.1a***	10.8 ± 2.9b***	8.8 ± 1.2b	9.6 ± 1.1ba	10.5 ± 1.8a*	10.3 ± 1.4a*
ntf	22.3 ± 7.8b	64.4 ± 21.9a***	30 ± 11.4b	24.4 ± 8.7b	32.7 ± 7.4b	30.0 ± 9.6b	39.2 ± 10.6a**
nbf	3.1 ± 0.98b	5.6 ± 2.3a*	3.5 ± 1.5b				
nf	171.9 ± 34.6b	222.4 ± 32.2a**	227 ± 49.5a**				
f/m	0.059 ± 0.022a	0.066 ± 0.024a	0.064 ± 0.021a				

Values are mean ± SD. Values within a row followed by the same letter do not differ significantly at the $P < 0.05$ level by LSD pairwise comparisons (*, **, *** indicate significantly different from control group at $P < 0.05$, 0.01, and 0.001, respectively)

CD canopy diameter, *BL* the length of new branch, *BD* the diameter of new branch, *ratio (BD/BL)* the ratio of diameter to length of new branch, *nff* number of fruits per inflorescence, *nbf* number of branches producing fruit per tree, *ntf* number of total fruit load per tree, *nf* number of flowers per inflorescence, *f/m* the ratio of female flower number to male flower number

Fig. 1 Inflorescence structure of a representative normal *Jatropha* shrub (**a**) and soil drench paclobutrazol-treated shrub showing compaction of inflorescence due to shortening of peduncle (**b**) at 110 days after treatment

Fig. 2 Infructescence structure of a representative *Jatropha* at 110 days after treatment showing (**a**) fewer fruits in control shrubs and (**b**) compact bunch of more fruits in shrubs treated with 2 g paclobutrazol

Statistical Analysis

Analyses were performed with SPSS ver. 11.5 (SPSS Inc., Chicago, IL, USA). Data were log-transformed if necessary to ensure assumptions of normality and homogeneity of variances. Main factor effects were tested using one-way ANOVA. Individual treatment means were compared using the LSD (least significance difference) test.

Results

Effect of PBZ on the Vegetative Growth of *J. curcas*

Paclobutrazol applied in both forms retarded the growth of *J. curcas*. Soil drench PBZ exerted a much more severe suppression of vegetative growth than the foliar spray PBZ treatment (Table 2). In experiment A, the 2-g soil drench PBZ treatment retarded growth by decreasing both the length and the diameter of new branches, whereas the 3-g soil drench PBZ did not further enhance the suppression. In experiment B, foliar PBZ decreased the length but increased the diameter of new branches, and consequently increased the ratio of length/diameter of new branches, and these effects, with the exception of the increase in the diameter of new branches, were enhanced with the increasing dose.

Effect of PBZ on the Reproductive Behavior and Quality of Seeds of *J. curcas*

Compared with the control group, the *J. curcas* trees treated with PBZ produced compact inflorescences due to shortening of the peduncle (Fig. 1). The number of fruit per inflorescence (*nff*), the number of total fruit load per tree (*ntf*), and the number of branches producing fruit per tree (*nbf*) were significantly increased by the 2-g soil drench PBZ (Fig. 2), but the 3-g soil drench PBZ reversed the increases of these three parameters (Table 2). The *nff* was significantly increased by foliar spray PBZ, but showed no significant difference among the three foliar spray PBZ treatments. The *ntf* was only significantly increased at 1,200 ppm but was slightly increased by the other two foliar spray PBZ treatments. Soil drench PBZ treatments (both 2 and 3 g) did not significantly affect the female/male flower ratio (*f*/*m*) per inflorescence, but they significantly increased the number of flowers per inflorescence (*nf*) compared with the control group.

Soil drench PBZ decreased the weight and the size of seeds, as indicated by the reduction in the weight per 50 seeds and the length and the diameter of the seeds. On the other hand, soil drench PBZ significantly increased the seed oil content, with the highest oil content at the 2-g soil drench PBZ (Table 3). The acid value was significantly reduced with increasing dose of soil drench PBZ. Moreover, soil drench PBZ marginally affected the fatty acid content of oil but variably affected the major components of fatty acid. In comparison with the control group, both soil drench PBZ treatments resulted in little change in the palmitoleic acid contents, significantly decreased palmitic and linoleic acid contents, and considerably increased oleic acid content. Stearic acid content was increased only by the 2-g soil drench PBZ and was slightly affected by the 3-g soil drench PBZ (Table 4).

Effect of PBZ on the Seed Elements in *J. curcas*

Soil drench PBZ greatly affected the elements of the seed (Table 5). Both soil drench PBZ treatments resulted in little to no significant change in the N, P, and K contents of the seed but they decreased S and Cu contents. Seed Mn and B contents were significantly increased by the 2-g soil drench PBZ but were markedly reduced (Mn) or little affected (B) by the 3-g soil drench PBZ. Fe content was reduced by only the 3-g soil drench PBZ.

Discussion

Soil drench PBZ greatly retarded the growth of *J. curcas* as indicated by the reduction in the elongation and diameter of new branches (Table 2). PBZ retards growth by inhibiting gibberellin biosynthesis, which occurs through the inhibition of kaurene oxidase which catalyzes the oxidative reactions from ent-kaurene to ent-kaurenoic acid in the pathway leading to the production of gibberellins (Rademacher and others 1984; Graebe 1987). In addition, IAA is the major and most abundant auxin in plants and plays a key role in the regulation of plant growth and development, including cell enlargement and division (Moore 1989; Davies 1995; Lüthen and others 1999). PBZ can slow the movement of IAA in shoot tips and indirectly decrease IAA by reducing gibberellin content (Dalziel and Lawrence 1984; Browning and others 1992), which is thought to be associated with

Table 3 Effects of soil drench paclobutrazol on the quality of seed of *Jatropha curcas*

	Weight (g)	Length (mm)	Diameter (mm)	Oil content (%)	Acid value (KOH g^{-1})
0 ($g\ m^{-1}$ CD)	33.69 ± 0.65a	19.70 ± 0.39a	9.36 ± 0.38a	34.29 ± 0.36c	1.99 ± 0.06a
2 ($g\ m^{-1}$ CD)	31.22 ± 0.76b**	18.87 ± 0.36b***	9.14 ± 0.46b*	36.15 ± 0.55a**	1.52 ± 0.10b***
3 ($g\ m^{-1}$ CD)	29.60 ± 1.76b***	17.43 ± 0.41c***	9.08 ± 0.54b**	35.16 ± 0.34b*	1.26 ± 0.05c***

Values are mean ± SD. Values within a column followed by the same letter do not differ significantly at the $P < 0.05$ level by LSD pairwise comparisons (*, **, *** indicate significantly different from control group at $P < 0.05$, 0.01, and 0.001, respectively)

Table 4 Effects of soil drench paclobutrazol on the quality of the seed oil of *Jatropha curcas*

	Fatty acid (%)	Palmitic acid (%)	Palmitoleic acid (%)	Stearic acid (%)	Oleic acid (%)	Linoleic acid (%)
0 ($g\ m^{-1}$ CD)	98.26 ± 1.00a	13.27 ± 0.20a	0.78 ± 0.05a	6.24 ± 0.24b	39.95 ± 0.77b	38.02 ± 1.11a
2 ($g\ m^{-1}$ CD)	98.39 ± 0.60a	12.76 ± 0.22bc*	0.80 ± 0.04a	7.00 ± 0.35a*	43.68 ± 0.92a**	34.15 ± 0.85b**
3 ($g\ m^{-1}$ CD)	98.35 ± 0.80a	12.51 ± 0.21c**	0.77 ± 0.03a	6.86 ± 0.46ab	44.31 ± 0.70a***	33.90 ± 1.15b**

Values are mean ± SD. Values within a column followed by the same letter do not differ significantly at the $P < 0.05$ level by LSD pairwise comparisons (*, **, *** indicate significantly different from control group at $P < 0.05$, 0.01, and 0.001, respectively)

Table 5 Effects of soil drench paclobutrazol on the elements in the seed of *Jatropha curcas*

	N (%)	P (%)	K (%)	S (%)	Mn (mg kg^{-1})	Cu (mg kg^{-1})	Fe (mg kg^{-1})	B (mg kg^{-1})
0 (g m^{-1} CD)	2.95 ± 0.17ab	0.59 ± 0.03a	0.80 ± 0.03a	0.148 ± 0.005a	22.77 ± 0.60b	16.61 ± 0.09a	35.66 ± 1.2a	11.58 ± 0.22b
2 (g m^{-1} CD)	2.88 ± 0.04b	0.57 ± 0.01a	0.82 ± 0.01a	0.101 ± 0.008c***	43.23 ± 0.21a***	15.82 ± 0.20b**	35.16 ± 0.80a	13.89 ± 0.14a***
3 (g m^{-1} CD)	3.13 ± 0.10a	0.57 ± 0.04a	0.80 ± 0.03a	0.132 ± 0.002b*	15.39 ± 0.32c***	15.26 ± 0.23c***	25.80 ± 1.00b***	11.19 ± 0.43b

Values are mean ± SD. Values within a column followed by the same letter do not differ significantly at the $P < 0.05$ level by LSD pairwise comparisons (*, **, *** indicate significantly different from control group at $P < 0.05$, 0.01, and 0.001, respectively)

growth inhibition. In addition, PBZ was also reported to affect the water and nutrient uptake of plants by reducing xylem thickness, which could partially account for the restricted plant growth (Wang and Gregg 1989). Moreover, soil drench PBZ exerted much greater suppression on the growth of *J. curcas* than foliar spray PBZ. The greatest suppression of the growth of new branches in these two experiments was found with the 3-g soil drench PBZ treatment (suppressed by 63.7 %) and in the 1,200-ppm treatment (suppressed by 42.8 %). In addition, in contrast to the soil drench PBZ treatment, foliar spray PBZ increased the diameter of new branches (Table 3). Consistent with our results, soil drench PBZ has been found to be more effective than foliar spray applications in reducing plant size (Li and others 1989; Barret and others 1994, 1995; Singh 2000; Bañón and others 2002; Pardos and others 2005; Alkhassawneh and others 2006). This effectiveness may be directly related to the high persistence of PBZ in the soil (Jacyna and Dodds 1999; Sharma and Awasthi 2005) and plant organs (Gent 1997; Latimer and others 2003; Pateli and others 2004). Davis and others (1988) considered that when PBZ was applied to the soil there was a continuous supply that could be translocated acropetally from root to shoot via the xylem, thus maintaining the concentration of PBZ above the threshold required for inhibition of gibberellin biosynthesis.

Jatropha curcas has been characterized as a fast-growing shrub (Freitas and others 2011). The competition between vegetative growth and reproductive growth for water and plant hormones leads to a reduction in yield fruit quality and an increase in water requirements (Arzani 1994). PBZ treatment has been shown to increase fruit yield and suppress vegetative growth in several fruit trees such as peach, 'Crimson Gold' nectarines (Blanco 1988), and cherries (Kaska and others 1991). Similarly, in the present research, the fruit load was significantly increased with the 2-g soil drench PBZ and the 1,200-ppm foliar spray PBZ treatments (Table 2). The increases in the *nff* and the *nbf* most likely contributed to the increase in the *ntf* in the 2-g soil drench PBZ treatment (Table 2). The increase in *ntf* was also possibly related to the allocation of more carbohydrates to the fruits at the expense of shoot growth, which was reduced (Arzani and Roosta 2004). PBZ was reported to also possess florigenic properties (Asin and others 2007), which perhaps increased the flowering and fruiting in *J. curcas* (Table 2). The increase in *nf* (number of flowers per inflorescence) and the slight change in *f/m* under the soil drench PBZ treatment contributed to the increase in the *nff*. PBZ has been shown to increase the *nf* in several other plants (Banko and Bir 1999; Burnett and others 2000). In our study, the 2-g soil drench PBZ and the 1,200-ppm foliar spray were determined to be the optimal treatments for obtaining the highest fruit load per tree.

In contrast to our results, Ghosh and others (2010) reported that the yield of *J. curcas* in the year in which PBZ was applied was decreased by soil drench PBZ and slightly affected by foliar spray PBZ. In their study, the lowest dose of soil drench PBZ was 0.75 g (ai) m^{-1} CD and the highest dose of foliar spray PBZ was 500 ppm, which was respectively higher and lower than the PBZ applied in the present study [the highest doses of soil drench PBZ and foliar spray PBZ were 0.45 g (ai) m^{-1} CD and 1,200 ppm, respectively]. In Ghosh and others study (2010), the dose of soil drench PBZ was too high for *J. curcas*, whereas the doses of foliar spray PBZ might not be high enough to increase the yield. In the present study, all doses increased the number of fruits per inflorescence; however, only the 1,200-ppm dose significantly increased the fruit load. These results suggest that the effects of PBZ treatments on growth reduction and increased yield of *J. curcas* would vary depending on the dose or concentration, method, or site of application.

It is well known that PBZ treatment can not only improve crop yield, it can also increase the quality and size of the fruit (Blanco 1988; Martin 1989). However, there have also been studies suggesting that PBZ treatment decreased seed weight in maize (Bayat and Sepehri 2012) and white clover (Budhianto and others 1994). In the present study, soil drench PBZ decreased the weight and size of seed with increasing dose (Table 3). This appeared to closely correlate with the negative effects of soil drench PBZ on the contents of the nutrient elements of seeds (Table 5). PBZ was thought to be able to reduce the thickness and length of xylem cells and the growth of roots and consequently restrict water and nutrient uptake in the plant (Wang and Gregg 1989; Pardos and others 2005). In addition, triazols could influence root growth and morphology, which would alter mineral uptake and plant nutrition (Pequerul and others 1997). It was reported that PBZ decreased N, P, K, and Fe contents in 'Nemaguard' peach trees (Rieger and Scalabrelli 1990) and Cu content in the leaf of mango (Werner 1993), whereas PBZ increased levels of B and Mn in 'Nemaguard' peach trees (Rieger and Scalabrelli 1990), leaf of mango (Werner 1993), and pear trees (Wang and others 1985). The 2-g soil drench PBZ only markedly decreased the S and Cu contents in seed, whereas it increased the Mn and B contents in seed (Table 5). A higher dose (3 g) of soil drench PBZ most likely restricted the uptake of the nutrients more severely than the lower dose (2 g). It markedly reduced the contents of S, Mn, Cu, Fe, and B in seed (Table 5). However, both PBZ treatments hardly influenced the contents of the three macronutrient elements (N, P, and K) in seed, which could result from the retardant of seed growth that compensated for the reduction of the uptake of these three elements. Moreover, the application of PBZ was also thought to promote the export of N compounds to reproductive parts of the plant (Ghosh and others 2010). The depletion of plant-available PBZ from the soil, which resulted from leachate (Ochoa and others 2009), would be responsible for the increase in the N, P, and K contents of seed of *J. curcas* in the second year of PBZ application in the study by Ghosh and others (2010).

Consistent with the study of Ghosh and others (2010), PBZ treatment at a suitable dose (2 g) increased the oil content of seed, whereas a higher dose of soil drench PBZ (3 g) reduced the oil content of seed (Table 3). Also, soil drench PBZ improved biodiesel oil quality of seed in two respects. First, it significantly reduced the acid value, which is important because a high oil acid value makes it more difficult to produce the biodiesel. Second, it altered the composition of fatty acids such that there was a significant increase in stearic acid and oleic acid contents and a pronounced reduction in linoleic acid and palmitic acid contents. It is well known that the composition of fatty acids can affect biodiesel oil quality. Octane is a commonly used indicator of diesel fuel quality, especially the ignition quality, and the order of octane of fatty acid methyl esters from fatty acids was: stearic acid > palmitic acid > oleic acid > palmitoleic acid > linoleic acid (Knothe and others 2003; Bamgboye and Hansen 2008). Oleic acid could enhance low-temperature fluidity of biodiesel, whereas linoleic acid can reduce the oxidation stability of biodiesel (Park and others 2008). Thus, in this study, the quality of the seed oil was improved by the soil drench PBZ, which could result in an increase in the quality of the biodiesel produced from the seed oil.

Conclusion

Both soil drench and foliar spray PBZ retarded the vegetative growth and promoted the reproductive growth of *J. curcas*. Fruit load of *J. curcas* was significantly increased only by the 2-g soil drench PBZ and the 1,200-ppm foliar spray PBZ. However, the 2-g soil drench PBZ negatively affected the nutrient uptake of *J. curcas*, which would contribute to the suppression of the vegetative growth and the reduction in the weight and size of seed. The 3-g soil drench PBZ further enhanced these negative effects. It brought small declines in the S and Cu contents of the seed but greatly decreased the Mn (by 32.4 %) and Fe (by 28 %) contents of the seed. In addition, the seed oil content and quality were improved by the 2-g soil drench PBZ, but these positive effects were reversed by the 3-g soil drench PBZ. Lastly, soil drench PBZ arrested the growth and promoted fruiting of *J. curcas* more effectively than foliar spray PBZ. Soil drench is a feasible and effective application method of PBZ in *J. curcas* plantings.

The optimum time for soil drench PBZ application may be in the spring just before formation of leaves, and the optimum dose may be below 2 g but this needs to be explored further.

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