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Original article

Effects of sulfur and phosphorus application on the growth, biomass yield and fuel properties of leucaena (*Leucaena leucocephala* (Lam.) de Wit.) as bioenergy crop on sandy infertile soil

Songyos Chotchutima,[a] Sayan Tudsri,[a,*] Kunn Kangvansaichol,[b] Prapa Sripichitt[a]

[a] *Department of Agronomy, Faculty of Agriculture, Kasetsart University, Bangkok 10900, Thailand*
[b] *PTT Research and Technology Institute, PTT Public Company Limited, Ayutthaya, Thailand*

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A B S T R A C T

A field experiment was conducted to determine the effect of Sulfur (S) and Phosphorus (P) fertilizer on the growth, biomass production and wood quality of leucaena for use as a bioenergy crop at the Buriram Livestock Research and Testing Station, Pakham, Buriram province, Thailand during 2011–2013. The experiment was arranged in a split plot design with two rates of S fertilizer (0 and 187.5 kg/ha) as a main plot and five rates of P (0, 93.75, 187.5, 375 and 750 kg/ha) as a sub-plot, with four replications. The results showed that the plant height, stem diameter, total woody stem and biomass yield of leucaena were significantly increased by the application of S, while the leaf yield was not influenced by S addition. The total woody stem and biomass yield were also proportionately greatest with the maximum rate of P (750 kg/ha) application. The addition of S did not result in any significant differences in fuel properties, while the maximum rate of P application also showed the best fuel properties among the several rates of P, especially with low Mg and ash contents compared with the control (0 kg/ha).

Introduction

The use of biomass as a source of renewable energy is a potential way to mitigate climate change by reducing greenhouse gas emissions from fossil fuel combustion and to secure energy supplies (Gasol et al., 2009). Biomass can be burnt or gasified in gasification plants to generate electricity (Hughes et al., 2007). Biomass for electricity generation sourced from natural forest is undesirable, due to the possible associated risks of deforestation and the increased pressure on this resource (Abe et al., 2007). Fast-growing tree farming is likely to be the most sustainable method of fuel supply for biomass production. Leucaena (*Leucaena leucocephala*) is expected to become one of the major bioenergy crops because it is a fast-growing tropical tree (Tewari et al., 2004), its stems and branches can serve as biofuel for heat and electricity production (El Bassam, 2010) and it is a nitrogen-fixing tree, which can generally improve soil nutrient conditions (Abe et al., 2007).

The use of fast-growing trees as a source of biomass for bioenergy crop production has markedly increased in recent decades and this trend is likely to continue (El Bassam, 2010). To abate any conflict between food and bioenergy crops, many researchers have proposed the use of marginal and poor abandoned lands for biomass feedstock plantations (Schroder et al., 2008). Northeastern Thailand has large areas of sandy soil that is generally acidic making such soils infertile (Imsamut and Boonsompoppan, 1999). Radrizzani et al. (2010) reported that the major factors contributing to P and S deficiencies and affecting leucaena response were inherently low soil fertility, soil shallowness and soil acidity. Acid soil is one of the causes of reduced efficiency in the use of P (Fageria, 2004). Barker and Collins (2003) found that P is one of the most important fertilizers influencing biomass production and N_2 fixation in forage tree legumes. Phosphorus and S nutrient deficiencies limit plant growth directly and suppress the symbiotic N_2 fixation of leucaena (Shelton and Brewbaker, 1998; Radrizzani et al., 2010). Acid soil requires P and S to improve the soil conditions in order to increase legume growth, survival of root growth and N_2 fixation (Kisinyo et al., 2005). Gypsum reduces the acidity and also supplies both calcium (Ca) and S; S deficiencies normally occur in acid soils because the sulfate leaches through these soils relatively rapidly

* Corresponding author.
E-mail address: agrsat@ku.ac.th (S. Tudsri).

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(Barker and Collins, 2003). Legume trees have responded strongly to added S, and N_2 fixation is affected by S (Ezenwa, 1994). Shelton and Brewbaker (1998) reported that it is essential to add S and P fertilizer at planting (early growth) and after each harvest in sandy textured and acidic soil.

Nevertheless, too much P fertilizer increases the risk of environmental damage caused by P runoff, which can be a problem in utilizing biomass for bioenergy (El Bassam, 2010) and leads to a high cost. The wood quality of leucaena is related to the proper application of fertilizer as specifically, Lewandowski and Kicherer (1997) stated that biomass combustion quality depends on ash, nitrogen (N), S and chlorine (Cl), with high amounts of S causing problems regarding emissions of SO_x (Obernberger et al., 2006). Hence, an understanding of the optimum rate of fertilizer applications is desirable to help determine their impact on the environment as fertilizer application plays an important role in sustaining the energy production system.

To ensure the long-term sustainability of biomass production of leucaena in sandy soil, a small-scale field experiment was conducted in Buriram province in northeastern Thailand, to evaluate the potential of leucaena plantation on sandy soils as an additional source of income for crop-growing farmers. Moreover, only a few researchers in Thailand have focused on increasing the biomass production of leucaena by determining the requirements for the application of S and P under such conditions (Chotchutima et al., 2013). Thus, the objectives of this study were to evaluate the application of P and S fertilizer on the growth, biomass yield and fuel properties of leucaena for biomass production on acidic soils.

Materials and methods

Experimental site and design

The experiment was conducted on the Buriram Livestock Research and Testing Station, Pakham, Buriram province, Thailand under rain-fed conditions. The soil on the site was a sandy loam with pH 5.2. The soil consisted of organic matter (0.55%), 2 ppm of available P and 9 ppm potassium (K). A split plot in a randomized complete block with four replications was used to compare two strategies of S application as gypsum (S at 0 and 187.5 kg/ha) as a main plot and five rates of phosphorus fertilizer as triple superphosphate (P1, 0 kg/ha; P2, 93.75 kg/ha; P3, 187.5 kg/ha; P4, 375 kg/ha; and P5, 750 kg/ha) as a sub-plot and the size of each plot was 6 × 5.5 m.

Establishment and management

After preparing the area for the experiment, leucaena (*L. leucocephala*, cv. Tarramba) seeds were scarified, inoculated with rhizobium strain 3126 and then sown in polythene bags (size 10 × 23 cm). The seedlings were grown in a greenhouse for 1 month until they were transplanted into the field in March 2011 at a spacing of 1 × 0.5 m. The seedlings were irrigated from March to May 2011 and no further field irrigation was applied thereafter. Weeding was done manually in all the plots. The fertilizer treatments were applied by hand broadcasting 2 months after planting, including a broadcast application of KCl (0-0–60) at 250 kg/ha. All fertilizer treatments were applied after each harvest at the same rates of S, P and K.

Plant measurement

Plant data collection was done at 4 and 12 months after planting in the field. The parameters measured consisted of plant height, the stem diameter at breast height (130 cm above ground level) and sprout number, with all measurements undertaken on 10 randomly selected plants per plot. The plant height was measured from the ground level to the highest point of the plant using a graduated meter stick, the stem diameter was measured using a vernier caliper and the sprout number was determined based on the number of green sprouts at the main axis of the stump by direct counting. At 12 months after planting, 18 plants in each treatment were selected and cut at 50 cm above ground level using a handsaw. Each plant was partitioned into leaf (including the green stem), branch and woody stem. The fresh weight of every tree part was recorded immediately after harvesting using an electronic balance. The dry weight (DW) of the leaf, branch and woody stem were each determined after drying in a hot air oven at 70 °C for 2 wk and then the woody stem component was air dried again for about 3 months. The woody density was measured by the water-displacement method as described by Pottinger et al. (1998) and woody stems were also analyzed for carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and S content (ultimate analysis) using an elemental analyzer (LECO, 2003). The chemical composition of P, K, Ca, magnesium (Mg) and sodium (Na) was analyzed using the methods of the Association of Official Analytical Chemists (AOAC) (AOAC, 1980). The ash content was measured by a proximate analysis method and the heating value was determined using a standard bomb calorific combustion method (AOAC, 1980).

Statistical analysis

All data were subjected to analysis of variance appropriate for a randomized complete block design. The least significant difference at the 5% level was used to identify significant statistical differences.

Results

Rainfall distribution

In the establishment year (2011), the rainfall exceeded the long-term average at the start of the experiment, but there was no rainfall during the first two months followed by a little rainfall (5 mm in July 2011) (Fig. 1). Rainfall increased from August to October 2011 and the maximum rainfall occurred in September 2011 (243 mm). The only rainfall during November 2011 to February 2012, was 94 mm in January. After the first-year harvest in March 2012, there was a small amount of rainfall (33 mm) in March 2012 and the rainfall increased from April 2012 to June 2012 (99–181 mm). In both August and September, the amount of

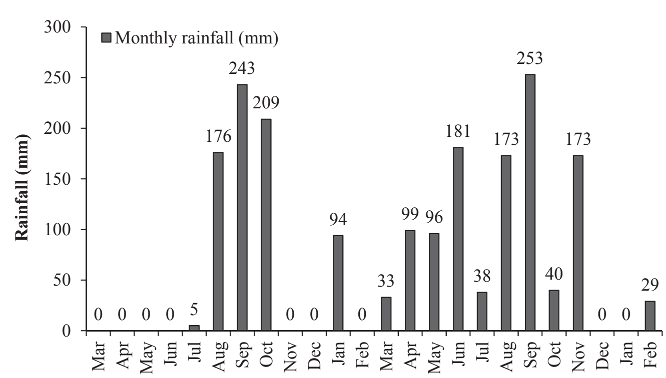

Fig. 1. Mean monthly rainfall from March 2011 to February 2013 at Buriram Livestock Research and Testing Station, Pakham, Buriram province, Thailand.

rainfall was 419 and 426 mm in 2011 and 2012, respectively. However, October 2012 had less rainfall at 40 mm than that in the previous year (219 mm). In contrast, November 2012 had much more rainfall at 173 mm than in the previous year. Annual total rainfall in the second year was greater at 1115 mm than that in the previous year (727 mm), due to the maximum monthly rainfall of 253 mm in September 2012. Just before the second year harvest, there was a little rainfall with 29 mm from December 2012 to February 2013.

Plant height, stem diameter and sprout number

The plant height increased significantly following the addition of S compared to the control (Table 1) in the 1st year. The plant height increased significantly with an increase in the P application rate. This increase in plant height was affected by the P application rate at both 4 and 12 months, with an increase with the P rate from 231 cm for the control (0 kg/ha) to approximately 380 cm for the maximum application rate of P, suggesting an interaction between the S application and the rate of P. In the 2nd year, the maximum P application rate of 750 kg/ha also resulted in the largest plant height (569 cm) whereas the control (0 kg/ha) recorded the lowest plant height (423 cm). On the whole, there were significant differences in the stem diameter between the addition and no-addition of S in both years.

The stem diameter tended to increase with an increase in the P application rate, with the highest stem diameter of 1.9 cm and 2.6 cm recorded at a P level of 750 kg/ha in the 1st and 2nd year, respectively. However, at 4 months in the 2nd year, there was an interaction between S application and the rate of P, while the stem diameter increased significantly with the increase in P application at 12 months in the 2nd year. Before harvest in the 1st year, the sprout number was not affected by the application levels of S and P fertilizer either at 4 or 12 months. Similar to the 1st year, the S treatment in the 2nd year did not affect the sprout number. The high P application rate produced no significant effect on the sprout number and the sprout number at 4 months was higher at 4–5 sprouts/stump than at 12 months at 2–3 sprouts/stump for all treatments.

Yield and yield component

The results indicated a strong relationship between the fertilizer application and the productivity of leucaena and there was no interaction between S application and the rate of P application. The application of S significantly improved the leaf and total biomass yield of leucaena compared to the control (no added S) in the 1st year (Table 2). The response to applied P was equal to the response to S; the maximum rate of P (750 kg/ha) showed the highest leaf, branch, woody stem and total biomass yields (2.1 t/ha, 1.0 t/ha, 5.7 t/ha and 8.7 t/ha DW, respectively). Similar to the 1st year, the S application in the 2nd year exhibited higher branch, woody stem and total biomass yields than in the control. In the 2nd year, the highest yields of leaf, branch, woody stem and total biomass were recorded at the maximum application rate of P (750 kg/ha). On the whole, the total biomass production was significantly influenced by fertilizer application. The total leaf yield was unaffected by the level of S application treatment, while S application generally showed greater total branch, woody stem and biomass yields than the control. The total leaf, branch, woody stem and biomass yields at the maximum application rate of P gave the highest yield among the application rates of P (4.9 t/ha, 3.1 t/ha, 25.5 t/ha and 33.3 t/ha DW, respectively).

Fuel properties

On the whole, the addition of S did not result in any significant differences in the elementary chemical composition and

Table 1
Plant height, stem diameter and sprout number of *Leucaena leucocephala* with different application rates of Sulfur (S) and Phosphorus (P) during 2 years.

	Plant height (cm)		Stem diameter (cm)		Sprout number (sprout/stump)	
	4 months	12 months	4 months	12 months	4 months	12 months
1st harvest						
A. Sulfur						
S+	101^{a}	351^{a}	–	1.8^{a}	1	1
S−	77^{b}	216^{b}	–	0.8^{b}	1	1
F-test	*	*	–	*	ns	ns
B. P rates (kg/ha)						
P1	79^{b}	231^{b}	–	0.9^{b}	1	1
P2	88^{b}	271^{b}	–	1.2^{b}	1	1
P3	81^{b}	258^{b}	–	1.1^{b}	1	1
P4	88^{b}	276^{b}	–	1.3^{b}	1	1
P5	109^{a}	380^{a}	–	1.9^{a}	1	1
F-test	**	**	–	**	ns	ns
A × B	ns	*	–	ns	ns	ns
2nd harvest						
A. Sulfur						
S+	339^{a}	582	2.1^{a}	2.7^{a}	4	3
S−	223^{b}	373	1.3^{b}	1.7^{b}	4	2
F-test	*	ns	**	**	ns	ns
B. P rates (kg/ha)						
P1	237^{c}	423^{c}	1.4^{c}	1.8^{c}	4	2
P2	276^{bc}	461^{bc}	1.7^{b}	2.1^{bc}	4	3
P3	253^{bc}	442^{bc}	1.5^{c}	2.1^{bc}	4	2
P4	299^{ab}	492^{b}	1.8^{ab}	2.3^{ab}	5	3
P5	340^{a}	569^{a}	2.0^{a}	2.6^{a}	4	3
F-test	**	**	**	**	ns	ns
A × B	**	ns	**	ns	ns	ns

*, ** = significantly different at the 0.05 and 0.01 probability levels, respectively; ns = non-significant difference; means in the same column followed by the same lowercase letter are not different at $p < 0.05$; S^{+}, S^{-} = S application as gypsum (S^{-} at 0 and S^{+} at 187.5 kg/ha); P1–P5 = rates of P application (P1, 0 kg/ha; P2, 93.75 kg/ha; P3, 187.5 kg/ha; P4, 375 kg/ha; and P5, 750 kg/ha).

Table 2
Yield component of *Leucaena leucocephala* with different application levels of Sulfur (S) and Phosphorus (P) during 2 years.

	Fresh weight (t/ha)				Dry weight (t/ha)			
	Leaf	Branch	Woody stem	Total	Leaf	Branch	Woody stem	Total
1st harvest								
A. Sulfur								
S+	5.0^{a}	1.6^{a}	8.1^{a}	14.7^{a}	1.9^{a}	0.7	4.4	7.0
S−	2.2^{b}	0.4^{b}	2.7^{b}	5.3^{b}	0.9^{b}	0.2	1.4	2.5
F-test	*	*	*	*	*	ns	ns	*
B. P rates (kg/ha)								
P1	2.6^{b}	0.5^{b}	3.2^{b}	6.2^{b}	1.0^{b}	0.2^{b}	1.6^{b}	2.8^{b}
P2	3.3^{b}	0.7^{b}	4.4^{b}	8.4^{b}	1.3^{b}	0.3^{b}	2.3^{b}	3.9^{b}
P3	3.4^{b}	0.8^{b}	4.6^{b}	8.7^{b}	1.3^{b}	0.4^{b}	2.5^{b}	4.1^{b}
P4	3.4^{b}	0.9^{b}	4.7^{b}	9.0^{b}	1.2^{b}	0.4^{b}	2.4^{b}	4.0^{b}
P5	5.4^{a}	2.1^{a}	10.2^{a}	17.7^{a}	2.1^{a}	1.0^{a}	5.7^{a}	8.7^{a}
F-test	**	**	**	**	**	**	**	**
A × B	ns	ns	**	ns	ns	ns	ns	ns
2nd harvest								
A. Sulfur								
S+	6.5	3.9^{a}	34.7^{a}	45.0^{a}	2.6	2.0^{a}	19.2^{a}	23.9^{a}
S−	3.5	1.2^{b}	12.6^{b}	17.3^{b}	1.4	0.6^{b}	5.7^{b}	7.7^{b}
F-test	ns	**	*	*	ns	**	*	*
B. P rates (kg/ha)								
P1	3.4^{c}	1.2^{c}	13.8^{c}	18.4^{c}	1.4^{c}	0.6^{c}	7.1^{c}	9.1^{c}
P2	4.3^{bc}	2.1^{b}	20.9^{b}	27.3^{b}	1.7^{bc}	1.1^{b}	10.6^{bc}	13.4^{bc}
P3	5.0^{b}	2.5^{b}	22.1^{b}	29.6^{b}	2.0^{b}	1.3^{b}	11.9^{b}	15.3^{b}
P4	5.3^{b}	2.9^{b}	24.4^{b}	32.5^{b}	2.1^{b}	1.5^{b}	12.9^{b}	16.5^{b}
P5	7.0^{a}	4.0^{a}	37.1^{a}	48.0^{a}	2.8^{a}	2.1^{a}	19.8^{a}	24.6^{a}
F-test	**	**	**	**	**	**	**	**
A × B	ns	ns	ns	ns	ns	ns	ns	ns
Total (1st–2nd harvest)								
A. Sulfur								
S+	11.5^{a}	5.5^{a}	42.8^{a}	59.7^{a}	4.5	2.7^{a}	23.6^{a}	30.9^{a}
S−	5.7^{b}	1.6^{b}	15.3^{b}	22.6^{b}	2.3	0.8^{b}	7.1^{b}	10.2^{b}
F-test	*	**	**	*	ns	**	**	*
B. P rates (kg/ha)								
P1	6.0^{c}	1.7^{c}	17.0^{c}	24.6^{c}	2.4^{c}	0.8^{c}	8.7^{c}	11.9^{c}
P2	7.6^{bc}	2.8^{b}	25.3^{b}	35.7^{b}	3.0^{b}	1.4^{b}	12.9^{bc}	17.3^{bc}
P3	8.4^{b}	3.3^{b}	26.7^{b}	38.3^{b}	3.3^{b}	1.7^{b}	14.4^{b}	19.4^{b}
P4	8.7^{b}	3.8^{b}	29.1^{b}	41.5^{b}	3.3^{b}	1.9^{b}	15.3^{b}	20.5^{b}
P5	12.4^{a}	6.1^{a}	47.3^{a}	65.7^{a}	4.9^{a}	3.1^{a}	25.5^{a}	33.3^{a}
F-test	**	**	**	**	**	**	**	**
A × B	ns	ns	ns	ns	ns	ns	ns	ns

*, ** = significantly different at the 0.05 and 0.01 probability levels, respectively; ns = non-significant difference; means in the same column followed by the same lowercase letter are not different at $p < 0.05$; S^{+}, S^{-} = S application as gypsum (S^{-} at 0 and S^{+} at 187.5 kg/ha); P1–P5 = rates of P application (P1, 0 kg/ha; P2, 93.75 kg/ha; P3, 187.5 kg/ha; P4, 375 kg/ha; and P5, 750 kg/ha).

heating value of the woody stem of leucaena. The C content varied from 44.1% to 44.4%, with no significant differences (Table 3). There were no significant differences in the H content which varied from 7.0% to 7.3% under the different application rates of P. A high N content was found in the treatments without S, but this was not significantly different from the S application. The different application rates of P were also not significantly different in their N content. The O content was not significantly different among the different rates of P (47.4%–47.8%). There were no significant differences in the S and P contents under the different application rates of P, which varied from 0.07% to 0.08% and from 0.07% to 0.19%, respectively. The K and Ca contents tended to decrease with increasing P rates, but the differences were not significant. With the increase in P level from 0 to 750 kg/ha, there was a corresponding decrease in the Mg content. The Na content was not significantly different among the different rates of P (0.01%–0.02%). The control (0 kg/ha) exhibited the highest ash content compared to the other P rates and there was an interaction between the application of S and P. The heating value was unaffected by P application, but tended to increase with the P rate from 4.28 kcal/g for the control (0 kg/ha) to 4.31 kcal/g at 750 kg/ha.

Discussion

The results indicated that the S application of 187.5 kg/ha as gypsum increased the plant height and stem diameter of leucaena. Leucaena responded to added S by producing greater stem diameters, with a strong relationship between the S application and stem diameter of leucaena. The minimum size of log wood required for a biomass gasification system is 2.5 cm (Arjhan et al., 2007). Therefore, the stem diameter from the application of S is suitable after 12 months. It is not surprising that there were positive effects on leucaena growth from the addition of fertilizer in the acidic soil, as the soil in this experiment was acidic (pH 5.2) and deficient in S (0.23 ppm). Probert and Jones (1977) reported that extractable S of 4 ppm was proposed to be critical for the growth of tropical legumes. Although the present study did not analyze the S concentration in the leaf tissue, the leucaena leaves showed symptoms of S deficiency (leaf chlorosis, yellow and stunted appearance in young leaves) without any S addition whereas the application of S resulted in no obvious foliar deficiency symptoms. However, the leaf S concentration in the leaf tissue was not a consistent predictor of S deficiencies (Radrizzani et al., 2010). The S application showed an overall higher total biomass yield

Table 3
Effect of Sulfur (S) application and different rates of Phosphorus (P) on elemental composition, ash and heating value (HV) in woody stem of *Leucaena leucocephala*.

	(% dry basis)											Heat value (kcal/g)
	C	H	N	O	S	P	K	Ca	Mg	Na	Ash	
A. Sulfur												
S+	44.35	7.38	0.57	47.64	0.07	0.05	0.24	0.10	0.13	0.01	1.46	4.33
S−	44.13	7.06	0.95	47.79	0.08	0.17	0.54	0.28	0.26	0.02	2.69	4.28
F-test	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
B. P rates (kg/ha)												
P1	44.33	7.19	0.92	47.48	0.08	0.07	0.51	0.29	0.25[a]	0.01	2.74[a]	4.28
P2	44.35	7.05	0.86	47.67	0.07	0.09	0.43	0.20	0.21[a]	0.02	2.02[bc]	4.30
P3	44.13	7.21	0.73	47.87	0.07	0.19	0.47	0.19	0.23[a]	0.02	2.13[b]	4.31
P4	44.13	7.31	0.72	47.77	0.07	0.13	0.32	0.14	0.17[ab]	0.01	1.95[bc]	4.31
P5	44.28	7.34	0.55	47.76	0.07	0.08	0.23	0.13	0.12[b]	0.01	1.52[c]	4.31
F-test	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	**	ns
A × B	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	**	ns

*, ** = significantly different at the 0.05 and 0.01 probability levels, respectively; ns = non-significant difference; means in the same column followed by the same lowercase letter are not different at $p < 0.05$; S^+, S^- = S application as gypsum (S^- at 0 and S^+ at 187.5 kg/ha); P1–P5 = rates of P application (P1, 0 kg/ha; P2, 93.75 kg/ha; P3, 187.5 kg/ha; P4, 375 kg/ha; and P5, 750 kg/ha).

compared to the no-S application. However, the low biomass yield in the 1st harvest also resulted from the late arrival and low level of rainfall. The amount of rainfall was too low for the optimal growth of leucaena in the 1st harvest. Thus, the high amount of rainfall in the 2nd harvest (1115 mm) resulted in a higher biomass yield than from the 1st harvest. Prinsen et al. (1992) reported that leucaena responds to S when soil water is not limiting and Radrizzani et al. (2010) indicated that rainfall use efficiency and symbiotic N_2 fixation by leucaena were restricted by an S deficiency. An additional yield increment of 43% (602 kg/ha) was reported to result from the S application (Radrizzani et al., 2010), while Prinsen et al. (1992) found that the S application increased the yield by 720 kg/ha in 8–12 yr-old leucaena stands.

Not only was there an increase in the soil S level, but gypsum also increased the soil pH and P sorption. The high content of Ca^{2+} in gypsum displaced Al^{3+}, Fe^{2+} and H^+ ions from the soil sorption sites (Hassett and Banwart, 1992). This resulted in a reduction in the soil acidity and increased P fixation. The soil P concentration was only 2 ppm in this experiment. Thus, the maximum rate of P (750 kg/ha) exhibited the highest plant height and stem diameter compared to the other rates during the 2 yr period. A suitable stem diameter (above 2.5 cm) was only found in the 750 kg/ha P application at the 2nd harvest. The maximum woody stem yield was obtained at the 750 kg/ha P application rate in both the 1st and 2nd harvests and an increased P rate increased the biomass yield, but did not increase the P content of the leucaena woody stem. Similar results were also reported by Khan et al. (1997), where there was an increased dry matter yield but no change in the leucaena leaf P content in response to the application of P on sandy loam soils. In contrast, Glumac et al. (1987) reported both increased leucaena yield and increased P content in the youngest fully expanded leaf in response to P application. The decrease in the woody stem biomass at a low P level was related to the lower P uptake, due to the acidic soil being low in phosphorus; thus, high rates of P should be applied (Shelton and Brewbaker, 1998). On low fertility soils, the quickest method to reach an optimum P level is through the application of a large amount of P (Barker and Collins, 2003). For a sandy clay loam soil (pH 6.5), Chotchutima et al. (2013) reported annual yields for the woody stem of 27.5 t/ha. However, a low biomass yield under a low P rate also resulted from the method of P application. The fixation of broadcast P is much greater than when the fertilizer is applied in bands (Chakwizira et al., 2009), while hand broadcasting of P was used in the present study. Wilson et al. (2006) indicated that crops utilize banded P fertilizer more effectively than broadcast fertilizer P on low soil P (10 ppm) sites.

The addition of S had no influence on the chemical composition of any of the elements in the woody stem. Similar results were also found in the ash content and heating value. The woody stem of leucaena consisted mostly of C, O, and H, which have a strong impact on its thermal value. The C content of softwood species is 50%–53% and that of hardwood species 47%–50%, due to the varying lignin and extractives content (Ragland et al., 1991). The contents of C and H are related to the heating value; in this study, these contents were about 44% and 7%, respectively. Ragland et al. (1991) reported that N ranges from 0.1% to 0.2%, the O content ranges from 40% to 44% while the S content was less than 0.1% in pine wood. As a legume tree species, leucaena wood may have a higher N content than other plant varieties reported in various studies (Ragland et al., 1991; Telmo et al., 2010). An increased P rate tended to result in a low N content in the woody stem especially at the maximum rate of P. However, none of the P application rates exceeded the critical value (1%) according to Obernberger et al. (2006). The S content was very low in the woody stem (0.07%–0.08%). Obernberger et al. (2006) found that an S content of more than 0.2% can result in SO_x and consequently, harmful SO_x emissions from the combustion of leucaena wood should be practically insignificant (El Bassam, 2010). The inorganic elements in the woody stem consisted mostly of P, K, Ca and Mg (Ragland et al., 1991), but Na was also present in lesser amounts. A high content of P in a fuel can crucially influence the combustion behavior as well as being responsible for the formation of low melting temperature ash (Steenari et al., 2009); however, the present study resulted in a low P content in the woody stem. The K content resulting from both S and P applications did not exceed the critical value (above 7%). An increased K content over 7% is very undesirable in power plant fuels as this can lead to a decreased ash melting point, which can cause slag and hard deposit formation in the furnace and boiler (Obernberger and Thek, 2004). The presence of Ca and Mg usually increases the ash melting point (Obernberger and Thek, 2004). The N, K and Mg levels tended to decrease with the increased application of P. In contrast, P had a generally positive and significant interaction with N, K and Mg. The positive interaction between P and macronutrients may have resulted from an improvement in the growth and yield of plants following P fertilization (Fageria, 2004). Na plays a major role in corrosion mechanisms and gives a tacky ash. However, the Na content was so low (0.01%–0.02%) that no problems should occur when firing it using traditional heating technologies (Hansen et al., 2009). The ash content of the samples from the maximum P application rate was low (1.52%) compared to the control rate with no P addition.

Demirbas (2004) reported that firewood has an ash content of 0.5%–3.0%, while straw can contain up to 8% ash. McKendry (2002) stated that an ash content above 5% resulted in the oxidation temperature being above the melting point of the biomass ash, leading to clinkering problems in the hearth and subsequent feed blockages. The ash consists partly of non-combustible minerals from the biomass, which requires ash removal equipment in the combustion system (Demirbas, 2004). All fertilization treatments showed heating values close to those reported in other studies (Rengsirikul et al., 2011; Chotchutima et al., 2013) and produced higher heating values than the guiding value at 3.35 kcal/g (Lewandowski and Kicherer, 1997).

The low biomass yield of leucaena was mainly caused by the infertile soil, resulting from the combination of a low pH and a sandy composition. The application of S (187.5 kg/ha) as gypsum and the maximum application rate of P (750 kg/ha) were suitable to produce a bioenergy crop on sandy soil. This treatment not only exhibited the highest total woody stem and biomass yields, but also resulted in suitable fuel properties (low Mg and ash content) for the woody stem.

Conflict of interest

The authors declare that there are no conflicts of interest.

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