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Effect of Soil Water Environment and Simulated Savanna Climate on Growth and Mineral Nutrition in *Jatropha curcas* L.

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Abstract

This study aimed to determine the optimal soil water conditions for *J. curcas* L. cultivation under the bi-annual rain seasons of the African Savannah climate. Changes in *J. curcas* L. seedling biomass and mineral nutrient uptake and movement patterns were examined under soil water matric potentials of -2.5, -2.9, -3.4 and -4.0kPa, and two rain seasons separated by a dry spell. The bi-annual savannah rain conditions were simulated using automated buried-type tensiometer system. During the first rain season (irrigation), -3.4kPa soil water matric potential showed the highest water-use efficiency (2.44 g dry weight L^-) and biomass yield (57.14g). Seedlings were variously affected by the subsequent dry spell, including total defoliation and stunting. On re-irrigation, seedling recovery (biomass and water use efficiency) was less as compared to the first rain season. Among the nutrients monitored, N, P and K were the most predominantly uptaken, with N showing the closest correlation with seedling growth. Soil matric water potential of －3.4 kPa is the optimum soil water environment for *J. curcas* cultivation in the savannah conditions; additionally, irrigation during the dry season is essential for a stable harvest.

Keywords: *Jatropha curcas* L., growth, water use efficiency, mineral nutrition, savanna climate

1. Introduction

Jatropha curcas L. belongs to the spurge family (*Euphorbiaceae*) and is an important biodiesel crop cultivated in different parts of America, Africa and Asia (Openshaw, 2000). It is sometimes categorized as a deciduous stem-succulent tree (Maes *et al.*, 2009b), and commonly used for several purposes such as; hedge to protect fields, green manure, oil-soap production, pharmaceuticals and biodiesel feedstock. It has a high potential for socio-economic development in terms of job creation for communities around plantations (Heller, 1996; Kumar & Sharma, 2008).

In sub-Saharan Africa, *J. curcas* has recently been adopted as one of the most suitable crops for biodiesel production (King *et al.*, 2009; Jingura, 2011; Jingura, Matengaifa, Musademba & Musiyiwa, 2011). It can be grown as a single stand on abandoned farmland, or used in marginal/waste land reclamation without competing for land currently used for food production. Moreover, it can adapt to poor soil fertility and drought/arid conditions (Augustus, Jayabalan & Seiler, 2002; Wang *et al.*, 2011). Water requirement for the crop is extremely low and can stand long periods of drought by shading most of its leaves to reduce transpiration loss (Reyadh, 2002).

A recent survey in Sub Saharan Africa however, revealed that farmers continuously irrigate *J. curcas* in both arid and semi-arid conditions and during both rainy and dry seasons of the year in order to maintain good yields. This is done to mitigate leaf shading which is triggered by water stress, especially during the dry season. The areas under *J. curcas* cultivation receive an annual rainfall requirement of about 944 mm (Maes, Trabucco, Achten & Muys, 2009a), and therefore require additional water supply during the dry season if good yields are to be obtained. Sustainable *J. curcas* production in these areas is uncertain unless water supply is supplemented during the course of cultivation. Assessment of different areas for optimal field water conditions might be necessary for sustainable *J. curcas* cultivation during both rain and dry seasons of the year. Meanwhile, some recent studies reported a variation in the yield and oil component of *J. curcas* seed as influenced by irrigation water levels (Kheira & Atta, 2009). Another study evaluated *J. curcas* seedling biomass production and distribution under different irrigation water scheduling under laboratory and field conditions (Behera, Srivastava, Tripathi, Singh & Singh, 2010; Maes, Achten, Reubens & Muys, 2011).

Additionally, Kheira and Atta (2009) estimated the weekly average water requirement for optimal *J. curcas* yield to be about 6 L. However, so far no studies have focused on optimum soil water potential for *J. curcas* growth. The aim of this study therefore, was to evaluate *J. curcas* performance under different soil water potential during both rain and dry seasons. Results of this study would be useful in guiding irrigation scheduling for sustainable *J. curcas* production in the arid and semi-arid regions of sub-Saharan Africa.

2. Materials and Methods

2.1 Nursery Cultivation

J. curcas seeds imported from Tanzania were sown in sandy soil in cell molding trays under greenhouse conditions at Tottori University, Japan. The textural composition of sandy soil was 95% sand, 1.3% silt, and 3.7% clay and soil texture was sandy. The wilting point and field capacity of this soil were 0.027 $cm^3\ cm^{-3}$ and 0.08 $cm^3\ cm^{-3}$ (these correspond to matric potentials of -1600 and -5.5 kPa), respectively. The chemical properties of sandy soil are as described by Uzoma *et al.*, (2011). After 6 weeks, *J. curcas* seedlings were transplanted to lager pots (30cm height, 12.5L) still in a sandy soil, and field capacity and nutrient supply maintained by automated fertilization (nutrients; total N: 1.52, P_2O_5: 0.70, K_2O: 2.36 g $plant^{-1}$) for a period of 62 days.

2.2 Experimental Treatments

J. curcas seedlings were cultivated under three different sets of simulated climatic conditions representing the short rainy (40 days), short dry (46 days) and long rainy (158days) seasons of Sub Saharan Africa. Detailed cultivation conditions including irrigation regimes and amount of cumulated irrigation each treatment during the entire experiment are given in Figure 1.

The short rainy season, represented by a short irrigation period was conducted under 4 different levels of soil water matric potential (W_1: -2.5, W_2: -2.9, W_3: -3.4 and W_4: -4.0 kPa: Each volumetric soil water content was W_1: 15%, W_2: 13%, W_3: 10% and W_4: 8%, respectively). The pots were fitted with and irrigated by a pair of micro-sprinklers (NETAFIM JAPAN Co.). Irrigation rate was controlled by an automated buried-type electric tensiometer system inserted at 10 cm below the soil surface (Nishihara, Inoue, Kondo, Takahashi & Nakata, 2001).

Irrigation was terminated at day 40, for short dry season simulation experiment (d). The treatment permutations in this season were represented as: W_{1d}, W_{2d}, W_{3d} and W_{4d}, with each pot fitted with a TDR sensor (Campbell Scientific Inc., USA) to measure volumetric soil water content. On day 86, *J. curcas* seedlings, which had survived the dry period were irrigated under－3.4kPa (W_3) again using the same irrigation system as earlier described for the next experimental season; the long re-irrigation (long rainy season). The treatment permutations were set at follows: $W_{1d3:}$ －3.4kPa, $W_{2d3:}$ －3.4kPa, $W_{3d3:}$ －3.4kPa and $W_{4d3:}$ －3.4kPa. The－3.4kPa matric potential was adopted here as it had showed the highest biomass yield in the first irrigation experiment. All treatments were replicated 5 times. During the entire experiment, air temperature was kept at 16－25 °C and relative air humidity (RAH) at more than 50%.

2.3 Sampling during Seedling Growth

Seedling leaf number, along with the fallen leaves were taken on a weekly basis for the entire cultivation period. Fresh biomass weight (including fallen leaves, stems, branches and roots was taken immediately after sample collection at 0, 40, 86 and 244 days. Total leaf area of each plant was recorded using an automatic area meter (AAC-410, HAYASHI DENKO CO., LTD. Japan). The different samples were then dried at 80°C for 48 h and dry weight recorded.

2.4 Plant Analysis

The dried biomass parts were ground into a fine powder prior to further chemical analysis. Total mineral nutrient contents potassium (K) and phosphorus (P) were measured after digestion with a mixture of hydrogen peroxide and concentrated sulfuric acid (99%). Potassium was determined by atomic absorption spectrophotometry on spectrophotometer (Z-2300, Hitachi, Tokyo, Japan). Phosphorus determined by the molybdenum-yellow method using a UV-visible spectrophotometer (U-2001, Hitachi, Tokyo, Japan). Total nitrogen content (N) was measured using an automated CN analyzer (Macro corder, JM1000CN, Yanaco, Kyoto, Japan).

2.5 Statistical Analysis

Each experimental data was subjected to statistical analyses using R version 2.12.0 (The R Foundation for Statistical Computing). The differences were significance by ANOVA ($P < 0.05$), the treatment means were separated using Tukey's multiple-range test. The linear regression analyses were used to check if the residuals showed a trend.

3. Results

3.1 Irrigation

Figure 1 shows the amount of cumulative irrigation water used for *J. curcas* seedling growth during the three different seasons. The W_1 soil matric potential treatment (－2.5 kPa) required the highest amount at 24.78 L plant^{-1}, while W_2, W_3 and W_4 treatments followed with 19.41, 16.94 and 15.09 L plant^{-1} respectively. During re-irrigation at the end of the cultivation cycle, irrigation water consumption was 42.09 L plant^{-1} (0.17 L day^{-1}) in W_{1d3} treatment (-3.4 kPa in re-irrigation period) and 36.72, 34.25 and 32.40 L plant^{-1} for W_{2d3}, W_{3d3} and W_{4d3} treatments respectively.

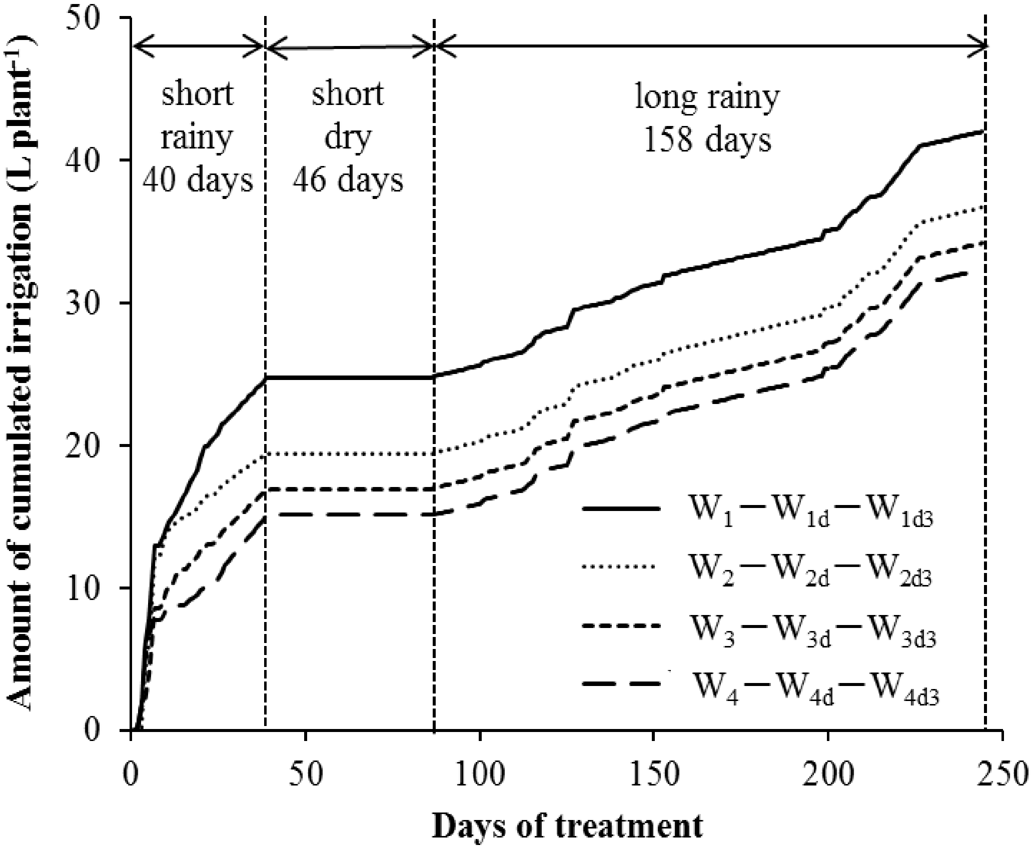


Figure 1. Cumulative irrigation for the entire experiment

3.2 Biomass Yield

Aboveground biomass yield of *J. curcas* seedlings is shown in Figure 2. At day 40, leaf count and leaf area were highest in W_3 treatment at 27.4 ± 1.9 and 2209 ± 113 cm^2 respectively. Leaf number declined immediately after cessation of irrigation (dry season), and on day 77, all leaves in W_{4d} treatment had been completely shed (volumetric soil water content was 4.95%). Leaves in the W_{2d} and W_{1d} treatments defoliated on days 78 and 84 (volumetric soil water content: 7.59% and 11.06%) respectively. Only W_{3d} treatment retained its leaves through the dry season (volumetric soil water content was 6.67%). Leaves in all treatments began to recover in the middle of re-irrigation.

Seedling height increased steadily under irrigation period with the highest of 69.1 ± 4.9 cm occurring in W_3 treatment (Figure 2b). Rate of height gain declined during the dry period, likely due to defoliation. The trunk diameter kept increasing in the first part of the dry experiment (Figure 2c), though on re-irrigation, trunk diameter remained more or less the same. A similar trend was observed in height.

3.3 Dry Weight

Table 1 shows dry weight of the various seedling parts under the different soil water potential and irrigation conditions. As seen earlier, dry weight yield was highest in the W_3 treatment at 57.14 ± 4.44 g, and so was water use efficiency (WUE) at 2.44 ± 0.26 g DW L^{-1}. On re-irrigation after the dry season, WUE tended to increase with decrease in amount of irrigation water. However, these values were less than those of the first irrigation period. Additionally, total dry weight under re-irrigation period was lower than that of initial irrigation period.

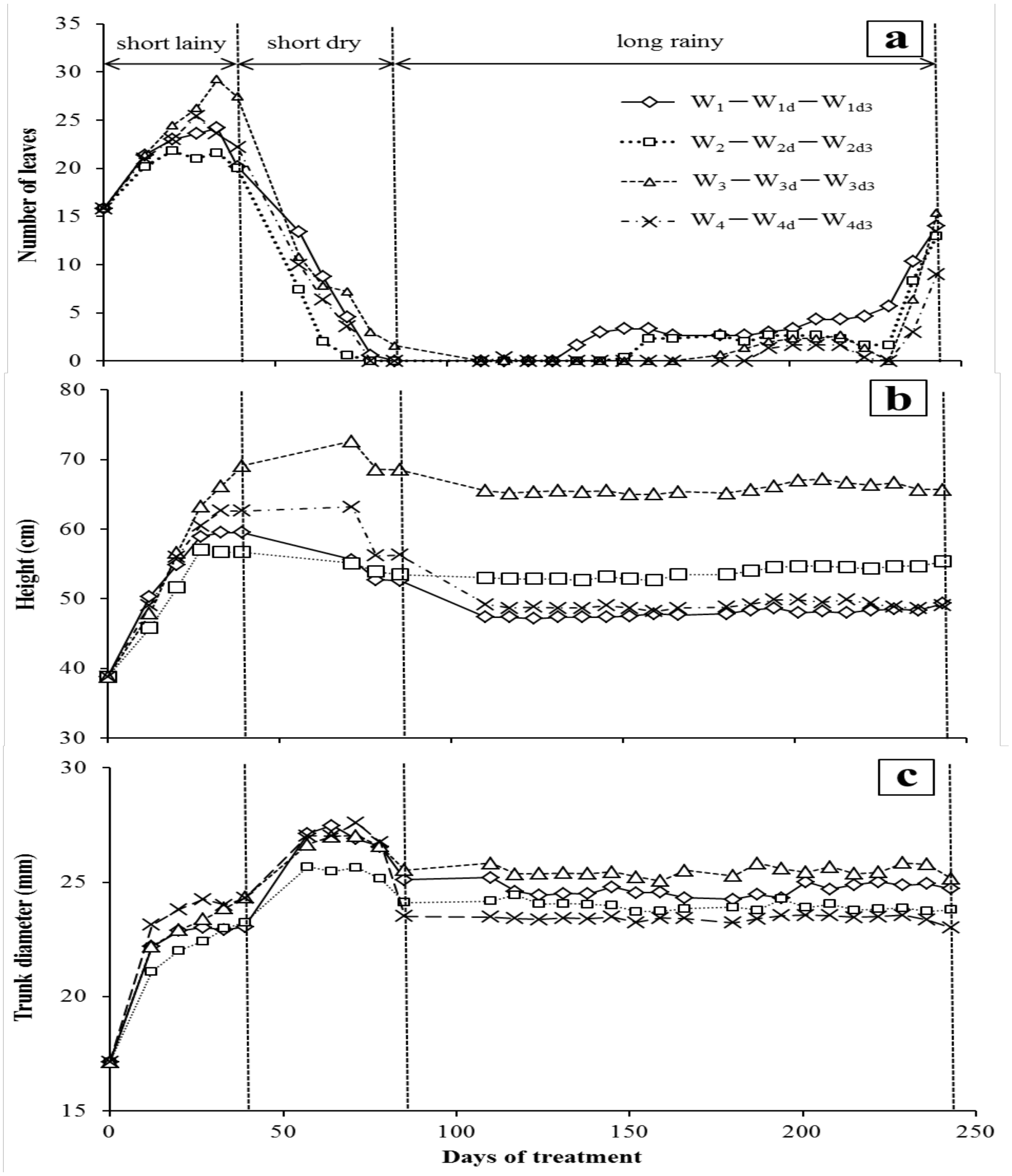


Figure 2. Changes in the number of leaves (a), height (b) and trunk diameter (c) of *J. curcas* seedlings

3.4 Mineral Nutrient Content

The mineral nutrient content N, P and K of the seedlings generally increased with cultivation time, but concentration varied in the different plant parts (Table 2). Nitrogen was highest in all parts under the －3.4 kPa matric water potential treatment (W_3, W_{3d} and W_{3d3}) during the entire cultivation cycle. Meanwhile, P content was observed to decrease during re-irrigation; K, uptake was highest and tended to increase with decreasing irrigation.

3.5 Biomass Yield and Mineral Nutrient Content

Relationship between the total dry biomass and N, P and K uptake during the entire experiment is shown in Figure 3. The linear regression analyses showed significant differences, especially total dry biomass for N uptake ($P < 0.01$, $R^2 = 0.709$).

Table 1. Dry matter yield**,** water content and water use efficiency (WUE) in the different parts of *J. curcas* seedlings

Season	Treatment	Dry weight				Water content			WUE
		Leaf	Stem	Root	Total	Leaf	Stem	Root	
		(g)				(%)			(g DW L^{-1})
Short rainy	W$_1$	11.86 ab	18.86 b	12.45 a	43.17 b	81.65 a	86.20 a	89.70 a	1.10 b
	W$_2$	11.11 b	19.17 b	12.53 a	42.81 b	82.93 a	85.50 ab	87.90 a	1.39 b
	W$_3$	15.33 a	26.56 a	15.25 a	57.14 a	81.89 a	84.34 b	84.22 b	2.44 a
	W$_4$	13.02 ab	21.46 ab	12.84 a	47.32 ab	83.13 a	82.76 c	83.32 b	2.09 a
	L	*	**	*	**	ns	***	***	***
Short dry	W$_{1d}$	0.00 a	24.87 a	18.11 a	42.99 a	-	81.55 a	83.18 a	-
	W$_{2d}$	0.00 a	20.42 a	15.09 a	35.51 a	-	82.83 a	82.25 ab	-
	W$_{3d}$	0.00 a	25.01 a	17.68 a	42.69 a	-	82.78 a	81.07 ab	-
	W$_{4d}$	0.00 a	21.31 a	15.84 a	37.15 a	-	79.93 a	80.52 b	-
	L	ns	ns	ns	ns		ns	**	
Long rainy	W$_{1d3}$	0.29 a	21.81 a	16.06 a	38.15 a	83.11 a	85.05 a	80.98 a	0.47 c
	W$_{2d3}$	0.32 a	22.30 a	15.02 a	37.65 a	82.00 a	84.43 a	80.03 ab	0.54 bc
	W$_{3d3}$	0.10 b	23.08 a	15.85 a	39.03 a	84.09 a	83.09 b	80.37 ab	0.67 ab
	W$_{4d3}$	0.08 b	22.37 a	17.06 a	39.50 a	78.13 b	82.46 b	79.56 b	0.77 a
	L	**	ns	ns	ns	**	***	*	**

Note: *, ** and *** indicate significant differences at $P< 0.05$, 0.01 and 0.001 respectively; ns indicates non-significant difference; Means with the different letters are significantly different at $P< 0.05$ (Tukey's multiple-range test); L indicates linear regression analysis.

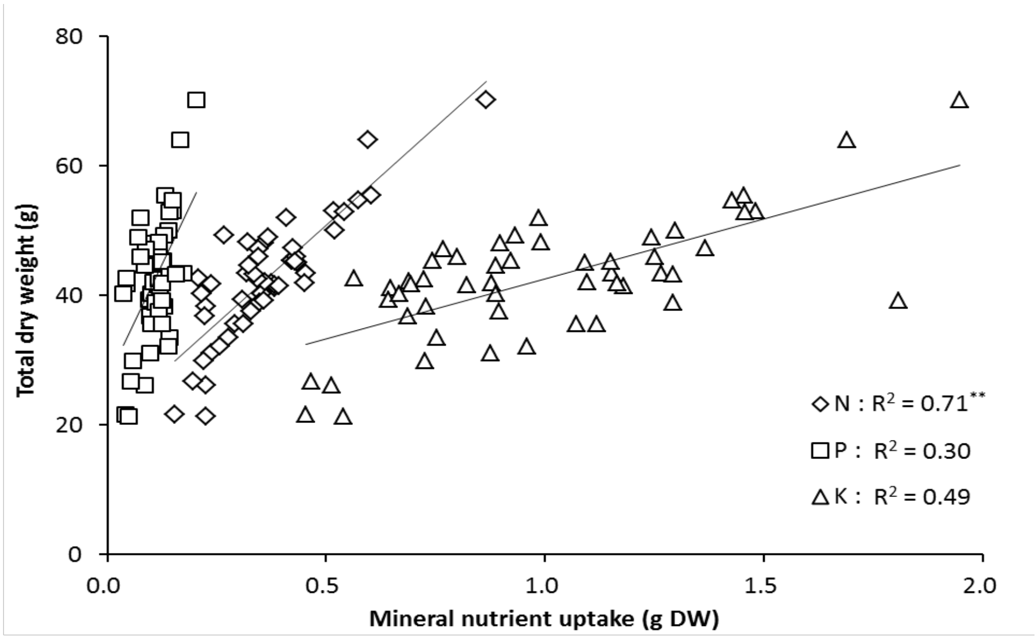
— indicates no data since leaves were fallen

Table 2. N, P and K content in the different parts of *J. curcas* seedlings

Season	Treatment	N (g kg^{-1} DW)			P (g kg^{-1} DW)			K (g kg^{-1} DW)		
		Leaf	Stem	Root	Leaf	Stem	Root	Leaf	Stem	Root
Short rainy	W$_1$	16.89 b	5.47 a	4.97 a	2.62 a	2.56 b	1.72 a	22.38 b	15.29 c	13.35 c
	W$_2$	18.15 ab	6.58 a	5.17 a	2.85 a	3.22 a	1.60 a	27.16 b	20.57 b	17.80 b
	W$_3$	20.98 a	7.14 a	5.70 a	3.27 a	2.58 b	1.76 a	33.50 a	25.79 a	21.58 a
	W$_4$	18.87 ab	6.12 a	5.32 a	3.30 a	2.88 ab	1.76 a	35.59 a	26.62 a	21.73 a
	L	*	ns	ns	*	ns	ns	***	***	***
Short dry	W$_{1d}$	-	6.13 b	6.81 a	-	3.44 a	1.93 a	-	21.48 b	15.19 c
	W$_{2d}$	-	9.35 a	7.28 a	-	4.12 a	2.86 a	-	29.10 ab	19.93 ab
	W$_{3d}$	-	10.73 a	7.85 a	-	3.55 a	2.01 a	-	32.40 ab	19.63 b
	W$_{4d}$	-	9.27 a	7.19 a	-	4.42 a	2.28 a	-	41.22 a	22.85 a
	L	-	***	ns	-	ns	ns	-	***	***
Long rainy	W$_{1d3}$	38.16 a	9.98 a	8.47 a	11.74 a	2.03 a	2.96 a	32.20 a	28.17 a	18.07 b
	W$_{2d3}$	40.39 a	10.82 a	9.78 a	9.98 a	2.04 a	2.61 a	35.33 a	30.60 a	22.40 ab
	W$_{3d3}$	41.83 a	11.86 a	10.22 a	15.49 a	2.36 a	3.35 a	39.30 a	34.57 a	26.30 ab
	W$_{4d3}$	38.49 a	11.34 a	10.19 a	10.31 a	2.10 a	3.13 a	41.90 a	35.57 a	27.90 a
	L	ns	ns	ns	ns	ns	ns	**	*	**

Note: *, ** and *** indicate significant differences at $P< 0.05$, 0.01 and 0.001 respectively; ns indicates non-significant difference. Means with the different letters are significantly different at $P< 0.05$ (Tukey's multiple-range test); L indicates linear regression analysis.

— indicates no data since leaves were fallen.



Note: ** indicates significant differences at $P< 0.01$

Figure 3. Regression analysis of total matter yield from N, P and K uptake in *J. curcas* seedlings

4. Discussion

4.1 Optimal Soil Water Environment

Biomass yield, water use efficiency and mineral nutrient uptake were highest under a soil water environment of −3.4 kPa (volumetric soil water content: 10%) during the first rain season. Average water consumption per week of this treatment was 3 L in the short rainy season; this is however, less than the 6 L week^{-1} reported by Kheira and Atta (2009) throughout the growing season. Under the other soil water environment conditions of −2.5 and −2.9 kPa volumetric soil water content > 13%, the soil aeration was greatly reduced (*ventilation of the soil of these treatments was lost)* thus the decrease in dry biomass, WUE and mineral nutrient uptake (Table 1, 2). This result is similar to a report by Heller (1996) in which *J. curcas* grew well on soil of good ventilation and drainage.

4.2 Response to Water Stress

Although biomass yield in the dry and re-irrigation experiments did not show significant differences among the treatments (Table 1), leaves in the −3.4 kPa were not completely shed (Figure 2). Moreover, Table 1 shows stem water loss rate was lowest (1.56 ± 0.41 %) here throughout the experiment period. This is in agreement with a study by Maes *et al.* (2009b) which stipulates the role of the *J. curcas* succulent stem in the water economy as balancing the small water losses through the leaves during drought. This result showed that proper management of this soil water matric potential enhanced drought tolerance. In the re-irrigation experiment, the cultivation days were 3 times more as compared to the initial irrigation experiment, though biomass yield and WUE of the latter were 1.1 ~ 1.5 and 2.2 ~ 3.6 times as much as those of the former respectively. Moreover, the leaves were completely shed in the dry spell, and it took time to sprout back on re-irrigation. Irrigation in the dry season was therefore important to maintain the above ground biomass of the plants. This supports findings by Maes *et al.* (2009b) that productivity of plantations in arid and semi-arid regions could decline unless additional irrigation was done.

During the dry season, it was observed that *J. curcas* increased mineral nutrient storage in the stem part (Table 2). This behavior is considered as a strategy of the succulent stem to minimize defoliation, and prepare for budding in the next rainy season.

4.3 Mineral Nutrient Uptake

Total K uptake and retention was highest (81.5 ~ 99.7% of the amount supplied), followed by N and P at 30.7 ~ 53.3 and 30.4 ~ 69.8%, respectively. Potassium was particularly predominantly high in leaves and stems, thereby making it easy to lose if branches/leaves were to be lost; for instance K content in fallen leaves was about 30.4 mg g^{-1} dry weight. It is therefore necessary to provide supplementary supply of this nutrient for long-term cultivation of *J. curcas* in semi-arid regions.

Meanwhile, there is potential for utilization of fallen leaves as organic sources of fertilizer in *J. curcas* plantations. Dange, Suthar and Reddy (2006) evaluated *J. curcas* leaves as organic manure, and found them effective. Additionally, *J. curcas* was shown to respond better to organic manure than mineral fertilizers on degraded soils (Francis, Edinger & Becker, 2005). Seed cake and seed hull of this tree are also good sources of compost (Sharma, Pandey & Lata, 2009; Das *et al.*, 2011); these are rich in essential mineral nutrients N, P and K.

Although K uptake was highest, it is the N uptake that correlated most with seedling growth (Figure 3). This is in agreement with a previous study that showed N to increase total dry biomass, whole plant water storage capacity, total evapotranspiration, irrigation water use efficiency and crop water use efficiency as compared to no N treatment (Yin *et al.*, 2012a; Yang, Li, Zhang & Liu, 2013). Tikkoo, Yadav and Kaushik (2013) had also showed seed yield and seed oil content to increase with amount of N fertilizer applied. Thus we suggested that N is the most important mineral nutrient in *J. curcas* cultivation. This is however in contrast to another study which suggested that the effect of N fertilization on the accumulation of osmolytes in the plant depended on drought stress level and N fertilization rate, and that applying a high rate of N fertilizer inhibited osmolytes accumulation under soil water stress conditions (Yin *et al.*, 2012b).

5. Conclusion

Basing on growth, water use efficiency and mineral nutrient uptake results, we conclude that the best soil water environment for *J. curcas* cultivation is −3.4 kPa (volumetric soil water content: 10%). This soil water condition prevented total leaf-shedding by saving water and mineral nutrients in the stem part; thus, soil water environment enhances drought tolerance. On the other hand, amount of K uptake was highest, however, it is N uptake that correlated most with growth. Therefore, we suggested that N is the most important mineral nutrient in *J. curcas* cultivation.

References

[1] Augustus, G. D. P. S., Jayabalan, M., & Seiler, G. J. (2002). Evaluation and bioinduction of energy components of Jatropha curcas. *Biomass and Bioenergy*, *23*(3), 161−164.

[2] Behera, S. K., Srivastava, P., Tripathi, R., Singh, J. P., & Singh, N. (2010). Evaluation of plant performance of Jatropha curcas L. under different agro-practices for optimizing biomass – A case study. *Biomass and Bioenergy, 34*(1), 30–41.

[3] Dange, V., Suthar, D., & Reddy, P. S. (2006). Biodiesel through Jatropha Curcas: A Critical Analysis. In B. Singh, R. Swaminathan, & V. Ponraj (Eds.), *Proceedings of the biodiesel conference toward energy independence—focus of Jatropha, Hyderabad, India, June 9–10* (pp. 31–36). New Delhi: Rashtrapati Bhawan.

[4] Das, M., Uppal, H. S., Singh, R., Beri, S., Mohan, K. S., Gupta, V. C., & Adholeya, A. (2011). Co-composting of physic nut (*Jatropha curcas*) deoiled cake with rice straw and different animal dung. *Bioresource Technology*, *102*(11), 6541–6546.

[5] Francis, G., Edinger, R., & Becker, K. (2005). A concept for simultaneous wasteland reclamation, fuel production, and socio-economic development in degraded areas in India: need, potential and perspectives of Jatropha plantations. *Natural Resources Forum*, *29*(1), 12－24.

[6] Heller, J. (1996). *Physic nut Jatropha curcas L.: Promoting the conservation and use of underutilized and neglected crops. 1*. Rome, Italy: International Plant Genetic Resources Institute.

[7] Jingura, R. M. (2011). Technical options for optimization of production of Jatropha as a biofuel feedstock in arid and semi-arid areas of Zimbabwe. *Biomass and Bioenergy*, *35*(5), 2127－2132.

[8] Jingura, R. M., Matengaifa, R., Musademba, D., & Musiyiwa, K. (2011). Characterisation of land types and agro-ecological conditions for production of *Jatropha* as a feedstock for biofuels in Zimbabwe. *Biomass and Bioenergy*, *35*(5), 2080－2086.

[9] Kheira, A. A. A., & Atta, N. M. M. (2009). Response of Jatropha curcas L. to water deficits: Yield, water use efficiency and oilseed characteristics. *Biomass and Bioenergy*, *33*(10), 1343–1350.

[10] King, A. J., He, W., Cuevas, J. A., Freudenberger, M., Ramiaramanana, D., & Graham, I. A. (2009). Potential of Jatropha curcas as a source of renewable oil and animal feed. *Journal of Experimental Botany*, *60*(10), 2897－2905.

[11] Kumar, A., & Sharma, S. (2008). An evaluation of multipurpose oil seed crop for industrial uses (Jatrophacurcas L.): A review. *Industrial Crops and Products, 28*(1), 1－10.

[12] Maes, W. H., Achten, W. M. J., Reubens, B., & Muys, B. (2011). Monitoring stomatal conductance of Jatropha curcas seedlings under different levels of water shortage with infrared thermography. *Agricultural and Forest Meteorology*, *151*(5), 554–564.

[13] Maes, W. H., Trabucco, A., Achten, W. M. J., & Muys, B. (2009a). Climatic growing conditions of *Jatropha curcas* L.. *Biomass and Bioenergy*, *33*(10), 1481–1485.

[14] Nishihara, E., Inoue, M., Kondo, K., Takahashi, K., & Nakata, N. (2001). Spinach yield and nutritional quality affected by controlled soil water matric head. *Agricultural Water Management*, *51*(3), 217－229.

[15] Openshaw, K. (2000). A review of Jatropha curcas: an oil plant of unfulfilled promise. *Biomass and Bioenergy*, *19*(1), 1－15.

[16] Reyadh, M. (2002). *The cultivation of Jatropha curcas in Egypt*. Undersecretary of State for Forestation, Ministry of Agriculture and Land Reclamation. Retrieved from http://www.fao.org/docrep/x5402e/x5402e11.htm.

[17] Sharma, D. K., Pandey, A. K., & Lata (2009). Use of *Jatropha curcas* hull biomass for bioactive compost production. *Biomass and Bioenergy*, *33*(1), 159 – 162.

[18] Tikkoo, A., Yadav, S. S., & Kaushik, N. (2013). Effect of irrigation, nitrogen and potassium on seed yield and oil content of Jatropha curcas in coarse textured soils of northwest India. *Soil and Tillage Research*, *134*, 142－146.

[19] Uzoma, K. C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., & Nishihara, E. (2011). Effect of cow manure biochar on maize productivity under sandy soil condition. *Soil Use and*

Management, 27(2), 205–212.

[20] Wang, W. G., Li, R., Liu, B., Li, L., Wang, S. H., & Chen, F. (2011). Effects of low nitrogen and drought stresses on proline synthesis of Jatropha curcas seedling. *Acta Physiologiae Plantarum*, *33*(5), 1591–1595.

[21] Yang, Q., Li, F. S., Zhang, F. C., & Liu, X. G. (2013). Interactive effects of irrigation frequency and nitrogen addition on growth and water use of Jatropha curcas. *Biomass and Bioenergy*, 59, 234－242.

[22] Yin, L., Liu, Y. A., Xie C. Y., Jianq, X., Wang, Y. J., Li, Y. H., Yan, Z., & Hu, T. X. (2012b). Effects of drought stress and nitrogen fertilization rate on the accumulation of osmolytes in *Jatropha curcas* seedlings. *Chinese Journal of Applied Ecology*, *23*(3), 632－638.

[23] Yin, C. Y., Pang, X. Y., Chen, K., Gong, R. G., Xu, G., & Wang, X. (2012a). The water adaptability of *Jatropha curcas* is modulated by soil nitrogen availability. *Biomass and Bioenergy*, *47*, 71－81.

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