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Investigating the variations of soil fertility and *Sorghum bicolor* L. physiological performance under plantation of some *Acacia* species

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Abstract: Taking the importance of agricultural production sustainability with limited resources to use efficiency in an arid area, afield experiment was designed to investigate the effect of three, *Acacia* trees (*Acacia nilotica*, *A. seyal*, and *A. tortilis*) planting combination on soil fertility and *Sorghum bicolor* L. growth and physiological performance. The sorghum planted in 7 strips between 14 rows of *Acacia* trees planting combinations and one treeless strip as control. *Acacia* species plantations significantly increase soil fertility in terms of available nitrogen (N), phosphorus (P), potassium (K) and organic carbon (OC) contents as compared to control, highest level of N and P content (59.01 ± 1.45 and 58.77 ± 1.10 mg/kg) was reported in strip between rows of *A. tortilis*. Although the highest net photosynthesis rate (P_n) and stomatal conductance (g_s) recorded in plants grown between rows of pure *A. torilis*, and rows of *A. torilis–A. seyal*, but different *Acacia* significantly enhanced sorghum growth and physiology with reference to net photosynthesis rate, stomatal conductance and chlorophyll fluorescence (*chl*F). The results stated linear relation between soil nutrients (N, P, K), P_n, and *chl*F increasing soil fertility improve physiological performance of sorghum. In conclusion, the three *Acacia* improve soil fertility and sorghum growth. Generally, this plantation trial can be environment-friendly alternative agricultural practices in Saudi Arabia or any area with a similar ecological condition to amend the soil and improve crop performance.

Keywords: agroforestry; canopy; climatic condition; Fabaceae; soil dryness; semiarid area

Worldwide, agriculture has to produce more food from a small area of land *via* adequate uses of natural resources therefore to meet the growing demands of the increasing population (Hobbs et al. 2007). Predictions suggest that climatic conditions will become more changeable and severe in the arid, semi-arid and sub-humid tropics (Rosenzweig et al. 2004). One of the effective solutions for using natural resources efficiently is the application of an agroforestry system in counties facing a shortage of rainfall and fertile land. Thus, agroforestry has numerous advantages, as increasing food production, conservation of biodiversity (George et al. 2012), soil enhancement (Udawatta et al. 2008) and resourceful use (Munz et al. 2014). Agroforestry plays a crucial role in multiuse and sustainable agriculture land (Schroth and da Mota 2013), by offering ecological services and environmental benefits (Branca et al. 2013). Many studies have revealed that in semi-arid and arid climates trees have great roles in reducing the adverse effects of climate and soil dryness (Anderson et al. 2001). Under trees canopy areas, the soil commonly had a higher quantity of organic matter and available nitrogen for plants (Smit and Swart 1994). Numerous factors are attributed to the soil fertility improvement under trees canopy such as dead parts of the *Acacia* trees (Amiotti et al. 2000). As general *Acacia* species are multipurpose trees provide a broad range of products (Pandey and Sharms 2003). The ability of *Acacia* trees to fix the atmospheric nitrogen (Chidumayo 2008) makes it one of the most suitable species for agricultural fields

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Table 1. Monthly average temperature, rainfall, and relative humidity

Parameter	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Air temperature (°C)	17.3	19.8	23.9	27.0	31.3	33.7	36.0	35.0	32.2	26.2	20.6	15.1
Rainfall (mm)	0.0	0.0	7.2	39.8	5.2	0.0	0.0	0.0	0.0	0.0	32.8	0.0
Relative humidity (%)	36	30	26	32	25	10	10	11	14	18	52	43

Source of data: https://www.pme.gov.sa/Ar/MediaCenter/OpenData

(Puri et al. 1994). In addition, trees shade improved water status, gas exchange and water use efficiency of plants and crops grown under trees canopies (Muthuri et al. 2005, Ong et al. 2006). Indigenous tree species, such as *A. tortilis*, have the potential to maintain or improve soil fertility while also increasing crop and forage production (Ludwig et al. 2001, Gemedo-Dalle et al. 2005). Desta et al. (2018) found the highest significant increase of soil organic carbon, total nitrogen available phosphorus, exchangeable calcium, exchangeable magnesium and cation exchange capacity under the canopy of *A. tortilis* as compared to open land. On the other hand, adding leaf leachate of *A. nilotica* to soil had improved soil nitrogen (N), potassium (K), phosphorus (P) and organic carbon (Choudhari et al. 2019). However, this study was conducted to assess the relationships between four *Acacia* species planting combinations, soil fertility, sorghum physiological performance in an arid area, the results may have used to expand agricultural production in areas with similar climate and poor soil.

MATERIAL AND METHODS

Experimental site. To investigate the effect of *Acacia* trees planting combination on soil fertility and crop performance of sorghum, *Acacia* trees stand plantation established in April 2010. The experiment conducted in Research and Experiments Station of the Faculty of Food Sciences and Agriculture, King Saud University, near Riyadh city, Saudi Arabia. The site characterised poor soil and adverse climate conditions such as high temperature, low relative humidity, and very low rainfall during the cropping period July–September (Table 1).

Experiment layout. Bare land (90 × 90 m = 0.81 ha) was prepared, after that seedling of exotic *A. nilotica*, *A. seyal* and indigenous *A. tortilis* were planted in rows (distance between each row was 6.5 m, and distance between each tree was 5 m. Each two rows planting combination represented one treatment (Figure 1, Table 2). Trees irrigated two times per week, leaves and twigs used as mulch while all woody branches removed. When trees exceeded the

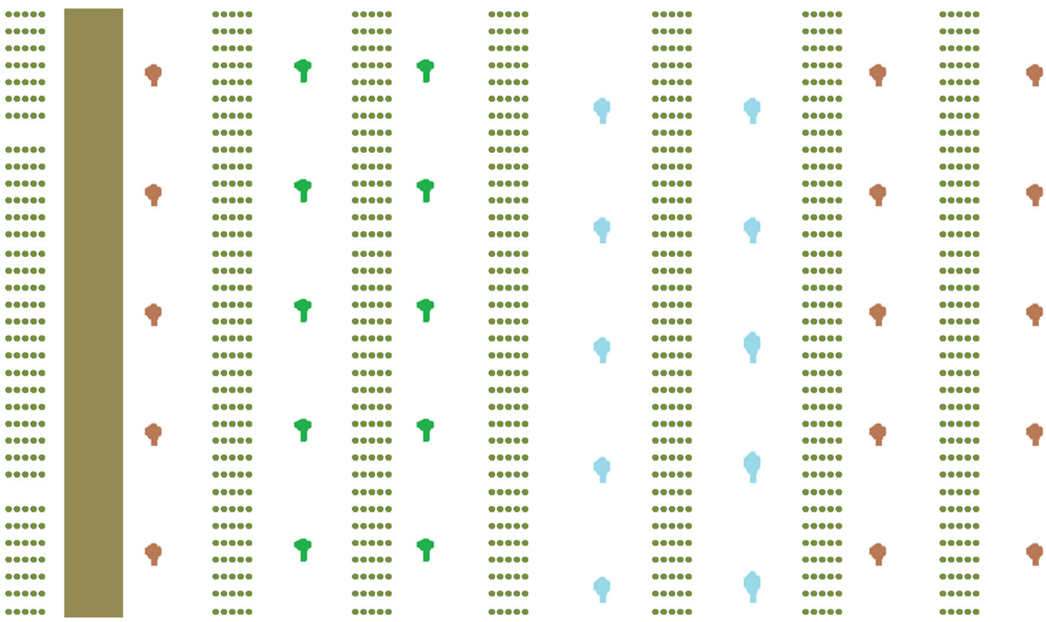

Figure 1. Illustration of experimental design: – *Acacia nilotica*; – *A. seyal*; – *A. tortilis*; ● sorghum, ■ buffer strip

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Table 2. Description of treatments (trees planting combination) and strips

Treatment	Treatments description
TR1	two rows of *Acacia nilotica*
TR2	two rows of *A. nilotica* and *A. seyal*
TR3	two rows of *A. seyal*
TR4	two rows of *A. seyal and A. tortilis*
TR5	two rows of *A. tortilis*
TR6	two rows of *A. tortilis* and *A. nilotica*
TR7	two rows of *A. nilotica* and treeless
C	control (treeless area)

Strip description: width – 6.5 m; length – 50 m; area of one treatment – 325 m^2; total cropped area – 2 600 m^2

juvenile stage (i.e., DBH (diameter at breast height) > 5 cm), Table 3 showed morphological characteristics of trees. After establishment trees stand, on 10th July, sorghum seed was sown in strips between trees rows, the distance between trees row, and the strip was 1.5 m to avoid complete shading of trees crown (Table 4).

Soil available nutrients (N, P, K) and organic carbon. For estimation of soil fertility, soil samples were taken at 1–30 cm soil depth from strips between different trees rows. Available P was determined according to the method of Silva et al. (2007) by the removal of soluble salts, carbonates, organic matter and iron oxides, using Ni-filtered Cu α radiation. The X-ray diffraction analysis carried out on the Mg-saturated air-dried, Mg-saturated glycerol solvated and K-saturated air-dried samples. For estimation of N and K samples were digested using the Kjeldahl wet oxidation process as described by Blakemore et al. (1987). Nitrogen in the sample converted to NH_4-N by sulphuric acid digestion in the presence of a copper catalyst, sodium sulphate, N in the digest is determined colorimetrically as NH_4-N using the indophenol reaction with sodium salicylate and hypochlorite, and P measured in the digest using optical emission spectroscopy using spectro Genesis ICP-OES (Mahwah, USA). While the determination of organic carbon (OC) estimated by using the method described by Jackson (1967).

Fresh weight. At the maturity stage, the plants in each square meter were harvested (all parts of the plant stem, leaves using as forage) and weighted directly by two decimal balance.

Gas exchange measurement. For the assessment of physiological performance of *Sorghum bicolor* under three *Acacia* species plantation, handheld photosynthetic system (CI-Handheld photosynthetic system, CID, Inc., Camas, USA) used to measure net photosynthetic rate (P_n), and stomatal conductance (g_s) under natural light conditions (at 9–11 a.m.) from the seven plants from each strip between trees rows.

Chlorophyll fluorescence. Chlorophyll fluorescence (*chl*F) measurements were performed on the middle part of adaxial leaf blades away from the main leaf vein fluorescence measurements that were performed with handle OS-30p+Chlorophyll Fluorometer (Opti-Sciences, Inc., Cary, USA). Chlorophyll fluorescence measurements were taken after the leaf pre-darkening (place a leaf into a dark adaptation clip with the slider closed and dark-adapted for 20 min using colored adaptation leaf clips), followed by a short exposure to saturating light intensity (μmol/m^2/s). All the physiological parameters measured during the growth stage (pre-flowering).

Experimental design and statistical analysis. The experiment was layout as a complete randomized design (CRD), each strip between one or two species considered as treatment plus control (treeless strip). All tested physiological traits of sorghum were statistically analysed by the SAS program. ANOVA was used to test variations between trees planting combinations at $P < 0.05$. *LSD* (least significant difference) test was used for mean comparison. A comparison was made between net photosynthetic rate, chlorophyll fluorescence and soil available N, P and K contents using simple linear regression analysis.

RESULTS

Soil available nutrients (N, P, K) and organic carbon. The *Acacia* trees species planting combinations significantly increased soil fertility between trees rows in terms of available N, P, K and organic

Table 3. Morphological characteristics of the stand (average height, diameter at breast height and crown diameter)

Species	Height (m)	Diameter at breast height (cm)	Crown diameter (m)
Acacia nilotica	6.54	6.57	2.84
A. seyal	5.60	6.50	3.14
A. totrtilis	4.97	5.84	2.67

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Table 4. Effect of *Acacia* species on soil available nutrients (NPK) and organic carbon

Treatment	Available nutrient (mg/kg)			Organic carbon (%)
	nitrogen	phosphorus	potassium	
TR1	29.69 ± 1.08^{bc}	32.50 ± 1.22^{bc}	78.35 ± 1.53^{c}	3.52 ± 0.21^{ab}
TR2	47.11 ± 1.65^{ab}	40.86 ± 2.08^{b}	114.33 ± 2.52^{ab}	6.17 ± 0.75^{a}
TR3	36.61 ± 1.31^{bc}	36.33 ± 1.43^{b}	94.40 ± 1.47^{bc}	3.66 ± 0.34^{ab}
TR4	46.54 ± 1.81^{ab}	37.37 ± 0.64^{b}	126.23 ± 2.04^{a}	3.34 ± 0.36^{ab}
TR5	59.01 ± 1.45^{a}	58.77 ± 1.10^{a}	119.00 ± 2.59^{a}	3.57 ± 0.46^{ab}
TR6	35.31 ± 1.34^{bc}	36.50 ± 1.40^{b}	88.74 ± 2.01^{c}	3.51 ± 0.42^{ab}
TR7	24.87 ± 1.49^{c}	24.23 ± 1.58^{c}	117.67 ± 2.00^{a}	3.14 ± 0.17^{b}
C	8.75 ± 0.95^{d}	8.73 ± 1.05^{d}	8.01 ± 0.80^{d}	0.34 ± 0.04^{c}
P-value	< 0.0012	< 0.0001	< 0.0001	< 0.0280
Least significant difference	18.598	9.2649	21.654	2.9395

carbon as compared to soil in the control strip (treeless area). The highest content of available nitrogen (59.01, 47.11, and 46.54 mg/kg) was recorded in strips between rows of indigenous species *A. tortilis* (TR5), *A. nilotica* and *A. seyal* (TR2), and the strip between *A. seyal* and *A. tortilis* (TR4), respectively. The lowest nitrogen content (8.75 mg/kg) recorded in the control strip (Table 3). The same trend was noticed in case of available P. K with the exceptional case of soil between *A. seyal* and *A. tortilis* (TR4) which had the highest content of K (126.237 mg/kg) as compared to all treatments. In the case of organic carbon content, all soil between strips of trees was higher than TR7 and control soil (Table 4).

Gas exchange. The analysis of variance revealed that the four tree species planting combination had significantly ($P < 0.0001$) affected gas exchange parameters, such as net photosynthetic rate and leaf stomatal conductance of sorghum plants. Net photosynthetic rates were significantly higher in sorghum plants grown in strips between two rows of *A. seyal* and *A. tortilis* (TR4), two rows of *A. tortilis* (TR5), two rows of *A. tortilis* and *A. nilotica* (TR6), two rows of *A. nilotica* and *A. seyal* (TR2), respectively, as compared to plants grown between strips of other species and control plants while sorghum plants grown in strips between two rows of *A. tortilis* (TR5) and two rows of *A. nilotica* and *A. seyal* (TR2) had highest leaf stomatal conductance as compared to plants grown between rows of other species and control (Figure 2).

Chlorophyll fluorescence. As Figure 3A indicated, there were statistically significant relations between chlorophyll fluorescence and *Acacia* species planting

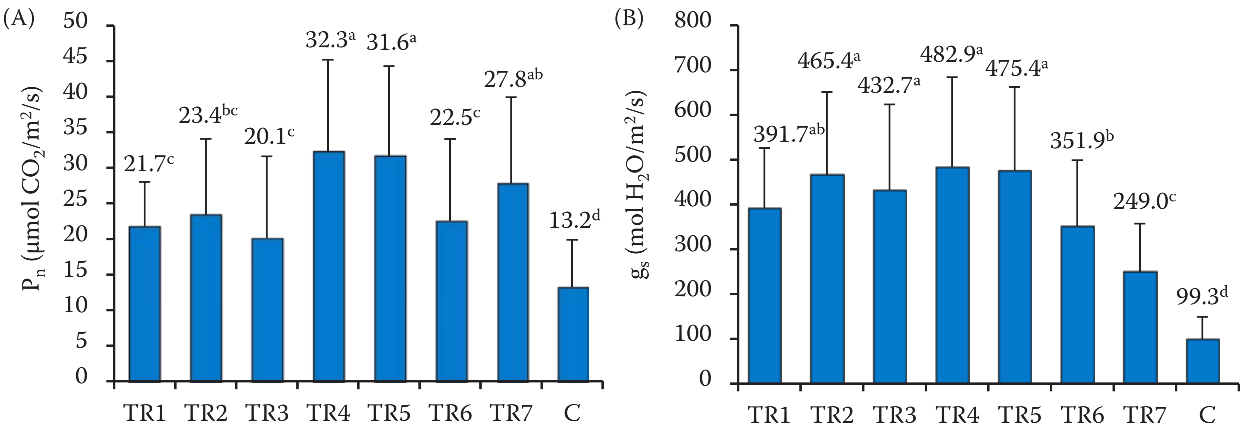

Figure 2. Effect of *Acacia* planting combination on (A) *Sorghum bicolor* net photosynthetic rate (P_n) and (B) *S. bicolor* leaf stomatal conductance (g_s). Bars represent means. Different letters indicate significant differences between trees row combination at $P < 0.05$

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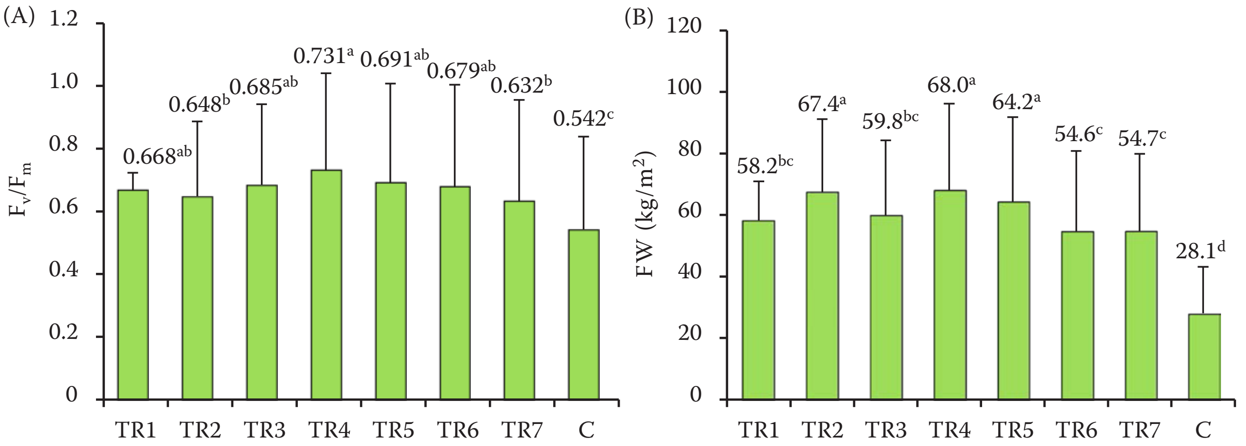

Figure 3. Effect of *Acacia* planting combination on (A) chlorophyll fluorescence (F_v/F_m) and (B) fresh weight (FW) of sorghum plants. Bars represent means. Different letters indicate significant differences between trees row combination at $P < 0.05$

combination. The sorghum plants grown between rows all of *Acacia* species had higher *Chl*F compared to plants grown in control strip. However, as overall, the highest *Chl*F as F_v/F_m ratio (0.731, 0.691 and 0.685) recorded in plants grown between rows of *A. tortilis* and *A. seyal*, a row of *A. tortilis* and a row of *A. seyal* respectively as compared to plants grown between other rows combination and control strip.

Growth performance. The fresh weight of sorghum plants followed the same trend of physiological traits, which is significantly enhanced by the three *Acacia* species and their arrangement. As plants growing between rows of *A. seyal* and *A. tortilis* had the highest fresh weight, 68.0 kg/m^2, then followed plants grown between rows of *A. tortilis* respectively and least fresh weight was recorded in plants grown in control strip (Figure 3B).

Relationships between soil nutrients and physiological parameters. As linear analysis revealed the soil, fertility in terms of available NPK strongly correlated with physiological traits of sorghum such as P_n and *Chl*F. All *r*-values are positive and greater than 0.5 (Figure 4). There was a strong correlation between P_n and nitrogen and potassium, but in the case of *Chl*F, the strong relations were between nitrogen and phosphorus.

DISCUSSION

The findings of this study related *Acacia* trees planting combination and soil fertility improvement especially indigenous one (*A. tortilis*), either as pure rows or in combination with other two exotic species (*A. nilotica* and *A. seyal*). The higher contents of nitrogen, phosphorus, potassium and organic carbon may due to adding trees pruning parts to the soil and the ability of *Acacia* species to fix nitrogen. The availability of nutrients to plants and soil organic carbon content is well documented, before by Worku et al. (2014) and Nsabimana et al. (2008) who concluded that increasing soil fertility was due to the addition of litterfall from trees and shrubs to the soil. The ability of *Acacia* to fix atmospheric nitrogen and their litter fall contributes significantly to increase soil fertility. In arid and semiarid areas, the soils under the *Acacia* canopy are usually improved and developed more than those outside the canopy, having higher nitrogen and water contents, Waldon et al. (1989) and Kassa et al. (2017), mentioned the role of agroforestry in maintaining soil fertility, and storing higher soil organic carbon and nitrogen. Trees increased soil organic carbon contents from pruning and litter (Gaafar et al. 2006). The highest gas exchange (P_n and g_s) recorded in sorghum plants grown in strips between *Acacia* trees, can be attributed to the higher content of nitrogen in the soil, which positively affects the leaves nitrogen content. This finding is in line with Shah et al. (2004) and Fletcher et al. (2013).

The results indicated that sorghum plants between rows of *A. tortilis* and *A. seyal* had the highest net photosynthetic rate, leaf stomatal conductivity as compared to plants grown between rows of other species and control. Increasing of plants stomatal conductance between rows of *Acacia* trees may be due to the reduction of temperature and wind un-

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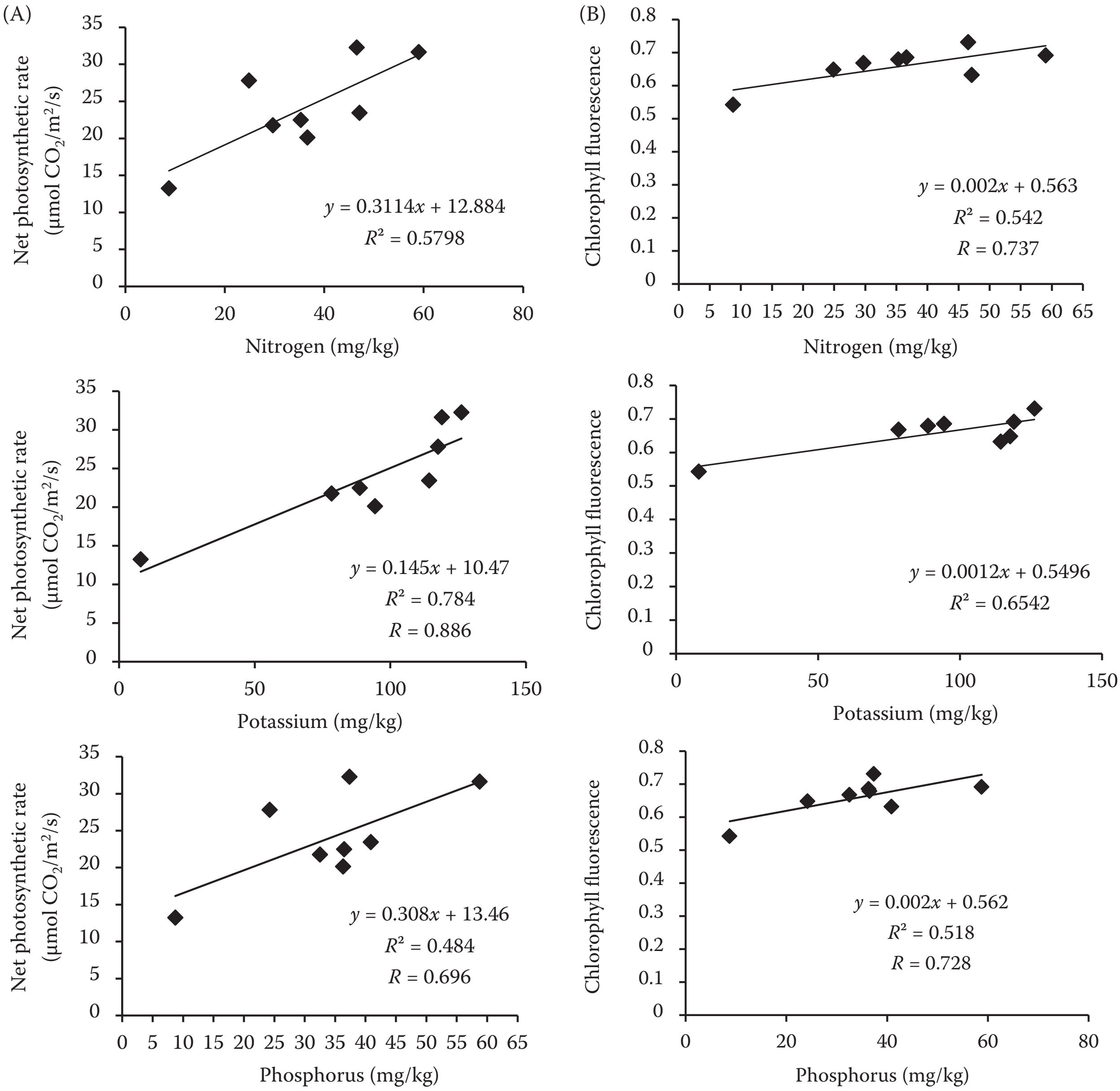

Figure 4. Linear relations between (A) net photosynthetic rate, and (B) chlorophyll fluorescence and soil available nutrients (NPK)

der trees canopy. This observation was in line with Masutha et al. (1997) who mentioned that *A. seyal* performed well in semi-arid conditions and has high rates of nitrogen-fixing in certain soils making it a good candidate for inclusion in agroforestry systems. Also, Abdallah et al. (2012) and Zeleke (2017) found that *A. tortilis* improve soil fertility and microclimate, compared to outside the canopy area. Chlorophyll fluorescence in term of the F_v/F_m was represented good indicator of soil fertility status, F_v/F_m is very useful in determining the suitability of a given agronomic species or varietal for a given abiotic environment, or assessing water or soil nutrient needs (Bertin et al. 1997, Abraham et al. 2003). Although all the species had increased sorghum fresh weight, the combination of *A. tortilis* and *A. seyal*, the results revealed the influence of the *Acacia* trees on sorghum crop performance under agroforestry could be explained by increasing nutrients between trees. The soil nutrients can improve the root system, physiological performance, so regulating crop yield (Usherwood and Segars 2001). Although all the species had increased sorghum growth, the combination of *A. tortilis* and *A. seyal* enhance soil fertility and

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hence plant physiology and growth under arid condition. The results established general linear relations between soil fertility (mainly NPK) and investigated physiological parameters of sorghum. These relations were mentioned by some authors such as Kattge et al. (2009) and Walker et al. (2014), they mentioned that there was the correlation between soil fertility, leaf, nitrogen as well as phosphorus content and both photosynthetic. The result of this study concluded that all *Acacia* trees combination specially the native one (*A. torlitis*), enhanced soil fertility and sorghum plant's physiological traits and yield in terms of fresh weight. The combination consisting of *A. seyal*, *A. tortilis* as pure rows or in combination with each other has much higher effects on soil fertility and sorghum crop physiological traits such as P_n and *Chl*F. The tree species, especially legumes, are essential for the improvement of soil fertility, particularly in the arid zone like Saudi Arabia, where the low soil fertility, shortage of rainfall and higher summer temperature, represented the major obstacles for agricultural production. Further research can be done in the same way or using other native legume species to explain the role of adapted native woody species on soil properties improvement and production of different crops in the area with the same ecological condition.

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