Pertanika J. Trop. Agric. Sci. 49 (5): 2545 - 2563 (2026)

PERTANIKA JOURNALS

TROPICAL AGRICULTURAL SCIENCE

Journal homepage: http://www.pertanika.upm.edu.my/

Growth, SPAD Index, and Nitrogen Use Efficiency of Two *Axonopus compressus* Variants Under Soil Mixture Ratios and NPK Fertiliser Regimes

Ting Zeng[1, 2]*, Abdul Shukor Juraimi[1], Nazatul Shima Naharudin[1], Mahmudul Hasan[3], and Muhammad Saiful Ahmad-Hamdani[1, 3]*

[1]*Department of Crop Science, Faculty of Agriculture, Universiti Putra Malaysia (UPM), 43400 Serdang, Selangor, Malaysia*

[2]*Guangxi Cultural Tourism and Wellness Integrated Development Center, Guilin Tourism University, 541004 Guilin, China*

[3]*Institute of Plantation Studies, Universiti Putra Malaysia (UPM), 43400 Serdang, Selangor, Malaysia*

ABSTRACT

Axonopus compressus is a widely used tropical turfgrass for landscapes and sports turf systems, but appropriate substrate-fertiliser combinations for newly developed variants remain insufficiently defined. This experiment assessed the growth responses of two mutant variants, A-40 and A-46, under three soil mixture ratios: S1 = 100:0 (sand: topsoil), S2 = 0:100 (sand: topsoil), and S3 = 70:30 (sand: topsoil). Nine NPK fertilisation regimes were evaluated, including an unfertilised control and four application rates (0.5×, 0.75×, 1.0×, and 1.5× of the recommended rate) of two fertiliser blends: NPK 15-15-15 + 2S (sulfur) and NPK 12-12-17 + TE (trace elements), each applied at four rates (GF1-GF4 and BF1-BF4). In A-40, BF3 showed the highest agronomic nitrogen use efficiency AE_N = 97.10 g biomass per g N, while BF4 produced the highest SPAD index (+67.9%) and leaf colour (+17.1%) compared with the unfertilised control. In A-46, BF2 and BF3 were the most efficient (AE_N = 80.22-79.32), whereas BF4 increased SPAD by 76.6%. SPAD index showed moderate to strong positive correlations with growth and biomass traits, particularly in A-46. S3 generally created a better growing medium; BF2 and BF3 provided relatively high biomass gain per unit of nitrogen input without requiring the highest fertiliser rate. These results provide practical guidance for variant-specific substrate-fertiliser management in tropical turfgrass systems.

Keywords: Agronomic nitrogen use efficiency, biomass, mutant *Axonopus compressus*, NPK fertilisation, soil mixture ratio

ARTICLE INFO

Article history:
Received: 01 July 2026
Accepted: 09 October 2026
Published: 30 October 2026

DOI: https://doi.org/10.47836/pjtas.49.5.22

E-mail addresses:
gs64190@student.upm.edu.my (Ting Zeng)
ashukur@upm.edu.my (Abdul Shukor Juraimi)
nazatul@upm.edu.my (Nazatul Shima Naharudin)
mdmahmudul@upm.edu.my (Mahmudul Hasan)
s_ahmad@upm.edu.my (Muhammad Saiful Ahmad-Hamdani)
* Corresponding author

e-ISSN: 2231-8542

© Universiti Putra Malaysia Press

INTRODUCTION

Turfgrass is an important plant for sustainable landscapes and has a wide range of applications. *Axonopus compressus* (Sw.) P.Beauv., commonly known as Cowgrass, is a stoloniferous perennial species of the Poaceae family. Under tropical conditions, *A. compressus* is commonly used in lawns, roadsides, golf courses, and stadium fields because of its low maintenance requirements, visual quality, and tolerance to high rainfall conditions (Wahid et al., 2023). Compared to other common turfgrass species such as *Cynodon dactylon* and *Zoysia* spp., it requires relatively low fertiliser input (Petrovic et al., 2005). In addition, *A. compressus* shows adaptability to different soil conditions, including sandy, loam, and clay soils (Azuddin et al., 2023). This makes it a cost-effective turfgrass species for recreational turf systems.

The growth quality of turfgrass is influenced by fertiliser and soil texture factors (Carlson et al., 2022). Soil texture influences water retention, aeration, and nutrient availability conditions, critical to root health and canopy development in turf systems (Hamarashid et al., 2010; Roberson et al., 2021). Nitrogen (N), phosphorus (P), and potassium (K) are essential nutrients required for turfgrass growth, including root and shoot development, leaf tissue expansion, and chlorophyll synthesis (Głąb et al., 2020; Shaddox & Unruh, 2021). Compound NPK fertilisers are widely used in turfgrass management because they provide major nutrients simultaneously. In practice, different compound NPK fertilisers are used in turfgrass management. NPK 15-15-15 + 2S provides a more balanced N, P, and K ratio, whereas NPK 12-12-17 + TE contains less N and P but a higher proportion of K together with trace elements (Alif & Amira, 2023). These differences in nutrient composition may affect plant growth, chlorophyll status, root development, and physiological responses. Comparing the two formulations therefore provides a basis for identifying a more suitable fertiliser regime for *A. compressus*.

Fertiliser management should not depend only on total biomass production. Depending on the fertiliser formulation and application rate, higher fertiliser input may increase biomass or leaf greenness, but greater nutrient input does not necessarily lead to a proportional increase in biomass. Agronomic nitrogen use efficiency (AE_N), calculated as the increase in total dry biomass per unit of nitrogen applied, was used to compare fertiliser efficiency (Bhatia et al., 2023). The SPAD meter is a rapid, non-destructive indicator of relative leaf chlorophyll content (Sim et al., 2015). It has been used for chlorophyll monitoring, nitrogen status and grain yield measurement for maize (Shivashankar et al., 2025), rice (Yuan et al., 2016), wheat (Islam et al., 2014), and other horticultural crops. Its application in turfgrass has been limited, particularly for narrow and flexible leaf types. However, the relatively broad leaves of *A. compressus* allow the SPAD sensor to cover the leaf surface in a practical way and to evaluate the response of this turfgrass to different fertilisation.

Improving soil mixture and fertiliser application rate is important for balancing turfgrass growth performance and resource-use efficiency. Over-fertilisation can increase management costs and nitrate leaching (Easton & Petrovic, 2004). Furthermore, over-fertilisation may result in poorer turf density and quality in poorly nutrient-rich soils. Most previous studies have explored single management factors or traits in assessing turfgrass performance (Kopp & Guillard, 2002; Springer et al., 2014; He et al., 2021) and the real landscape may not be fully represented by these features. A-40 and A-46 are two new *A. compressus* mutants selected following gamma-ray irradiation and showed desirable morphological and turf characteristics during previous screening. However, little is known about how these two mutants perform under different root-zone substrates and fertilisation regimes. Therefore, this study evaluated responses of two variants, A-40 and A-46, to different soil mixture ratios and graded NPK fertiliser regimes. Morphological traits, SPAD index, leaf colour, biomass traits, and AE_N were assessed to identify soil-fertiliser combinations that support turfgrass growth while improving nitrogen input efficiency. The findings provide practical information for variant-specific fertiliser and substrate management in tropical turfgrass systems.

MATERIALS AND METHODS

Experimental Site and Plant Material

This study was conducted at UPM-SATIRI Turfgrass Lab, Universiti Putra Malaysia, in Serdang, Selangor, Malaysia (2°59′N, 101°44′E). The place has a tropical rainforest climate. During the experimental period from April to September 2024, monthly maximum, average, and minimum temperatures ranged from 29.0 to 29.5 °C, 27.3 to 27.8 °C, and 25.5 to 25.9 °C, respectively. Monthly rainfall ranged from 152 to 206 mm (Figure 1). Temperature and rainfall data for the experimental period were obtained from the Visual Crossing Weather API using the coordinates of the experimental site. These conditions represented a typical tropical environment for evaluating the growth and physiological performance of *A. compressus* variants. All plant materials were cultivated and not collected from the wild. Both mutants A-40 and A-46 were developed from the original accession *A. compressus* through gamma irradiation mutation breeding at the Malaysia Nuclear Agency. Briefly, the original *A. compressus*

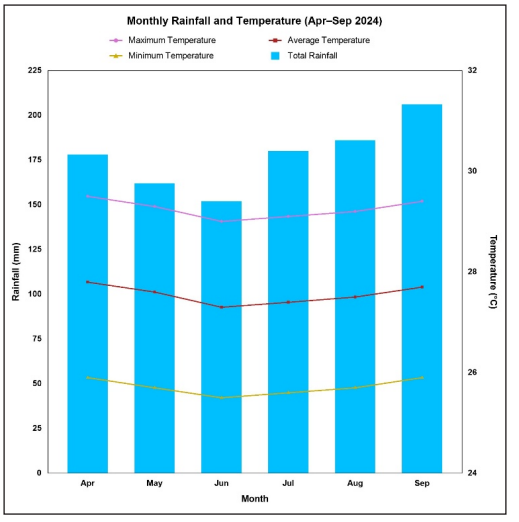

Figure 1. Monthly rainfall and temperature dynamics at the experimental site

individuals were exposed to gamma (γ) radiation at dosages of 200, 400, 600, and 800 Gy. All survivors were split into single nodes and regrown in pots at the UPM-SATIRI Turf Lab. The selection process continued until the 8th generation before the study was conducted.

Experimental Design and Treatments

The experiment was conducted in a split-plot within a randomised complete block design with three replications. Soil mixture ratio (three levels) was assigned to the main plots based on different soil mixture media: sand, topsoil, and a sand-topsoil mixture. Fertiliser treatment (nine levels) was assigned to the sub-plots based on one unfertilised control and different rates of two NPK fertiliser formulations. The experiment was conducted separately for the two variants, A-40 and A-46. Plants were established using a stolonising method. Ten stolon cuttings, each containing four internodes, were planted in plastic trays measuring 37 × 27 × 10 cm. Three soil mixture ratios were used: S1 = 100:0 (sand: topsoil), S2 = 0:100 (sand: topsoil), and S3 = 70:30 (sand: topsoil). The sand used was washed river sand with a particle diameter of <2 mm, while the topsoil was loam. Fertiliser regimes were applied across all soil mixture ratios and consisted of one unfertilised control and two NPK fertiliser formulations, each applied at four rates. NPK 15-15-15 + 2S, commonly known as NPK Green, was applied at 0.5×, 0.75×, 1.0×, and 1.5× of the recommended rate (GF1-GF4), while NPK 12-12-17 + trace elements (TE), commonly known as NPK Blue, was applied at the corresponding rates (BF1-BF4). The two compound fertilisers used in this experiment were purchased from Desyra Enterprise, Malaysia. The recommended rate was set at 0.25 kg N per 100 m² per month based on standard maintenance practice routinely used for A. *compressus* at the UPM-SATIRI Turfgrass Research Laboratory. The fertiliser amounts were calculated accordingly based on the nitrogen content (Table 1). To reduce nutrient loss caused by outdoor rainfall, trays were spaced 15 cm apart and placed on a raised, level platform lined with black plastic film.

Plants were manually watered three times daily during the first two weeks, at approximately 7:00, 10:30, and 5:00. From the third week onwards, watering was reduced to once daily at approximately 9:00 am. Fertilisation started two weeks after stolon establishment and continued every two weeks for 16 weeks. Growth parameters were recorded one week after each fertiliser application over eight sampling events, while biomass traits were measured at 20 weeks after planting. The traits included leaf length (LL), leaf width (LW), SPAD index (SPAD; relative chlorophyll content), number of leaves per plant (NLP), plant height (PH), and leaf colour (LC). At 20 weeks after planting, plants were evaluated for aboveground shoot fresh weight (SFW) and dry weight (SDW), as well as root fresh weight (RFW), root dry weight (RDW), root length (RL), and root volume (RV).

Table 1
Fertiliser formulation types, application rates, and nutrient quantities used per tray in experimental treatments

Code	NPK Fertiliser Regimes	Application Rate (× Recommended)	Single Tray Fertiliser Application Amount / Two Weeks (g)
F0	None	0×	0
GF1	(15-15-15+2S)	0.5×	0.42
GF2		0.75×	0.63
GF3		1.0×	0.84
GF4		1.5×	1.25
BF1	(12-12-17 +TE)	0.5×	0.52
BF2		0.75×	0.78
BF3		1.0×	1.04
BF4		1.5×	1.56

Note. F0 = unfertilised control; GF = NPK (15-15-15+2S); BF = NPK (12-12-17+TE). Numbers 1-4 indicate 0.5×, 0.75×, 1.0×, and 1.5× of the recommended rate, respectively

LL and LW were measured using a vernier calliper, while PH was measured using a ruler from the surface of the growing medium to the tip of the tallest leaf blade. NLP was determined by manually counting all fully expanded leaves on each selected plant. LC was evaluated with a TCM 500 NDVI Turf colour Meter (Spectrum® Technologies, Inc., USA). It was assessed using a rating scale from 1 to 9. A score of 1 represented a condition of wilting or bare ground. Scores ranging from 5 to 9 corresponded to colours from yellowish green to dark green, with a score of 5 signifying a noticeable increase in green foliage and a reduction in senescent leaves.

Determination of Relative Chlorophyll Content

Relative chlorophyll content was estimated using a SPAD meter (SPAD-502 Plus, Konica Minolta, Japan), following the general measurement approach described by Sim et al. (2015). The SPAD reading is a unitless index based on light transmittance through the leaf. Measurements were taken from the central area of the youngest fully expanded leaf to maintain consistency across samples. For each replicate, three readings were collected from different plants and averaged. All measurements were carried out in the morning between 8:30 and 9:00 under stable light conditions to reduce environmental variation and improve data reliability. SPAD index served as an indirect indicator of leaf greenness and nitrogen status during the experiment.

Determination of Biomass Parameters

All biomass traits were assessed using a randomly placed 100 cm² quadrat grid on the turf surface. Weight and root volume were expressed per unit area (g per 100 cm² and cm³ per 100 cm², respectively), while root length was expressed in centimetres (cm). At 20 weeks after planting, to determine the fresh and dry weights of the shoot and root components, samples were cleaned, and fresh weights were recorded separately. Subsequently, they were oven-dried at 65 °C for 72 hours to a constant weight. The volume of the roots was measured using a graduated cylinder and expressed in milliliters (mL), which is equivalent to cubic centimeters (cm³).

Calculation of Agronomic Nitrogen Use Efficiency

Agronomic nitrogen use efficiency (AE_N) was calculated following the general approach described by Li et al. (2023) with total dry biomass used as the biomass response variable. Total dry weight (TDW) was determined as the sum of shoot dry weight (SDW) and root dry weight (RDW) as in Equation 1:

$$TDW = SDW + RDW \quad [1]$$

Total nitrogen input for each tray was calculated using the fertiliser amount, nitrogen concentration, and number of applications. NPK 15-15-15 + 2S contained 15% nitrogen, while NPK 12-12-17 + TE contained 12% nitrogen. Since fertiliser was applied every two weeks for 16 weeks, the total nitrogen applied was calculated as in Equations 2 to 3:

$$N_{applied} = F_{amount} \times N_{concentration} \times n \quad [2]$$

$$AE_N = \frac{TDW_{fertili\ sed} - TDW_{F0}}{N_{applied}} \quad [3]$$

where F_{amount} is the fertiliser amount applied per tray at each application, $N_{concentration}$ is the nitrogen concentration of the fertiliser, and (n) is the number of fertiliser applications. For NPK 15-15-15 + 2S, ($N_{concentration}$) was 15%, whereas for NPK 12-12-17 + TE was 12%. Fertiliser was applied once every two weeks for 16 weeks; therefore, (n = 8).

Statistical Analysis

Data were analysed using analysis of variance (ANOVA) based on a split-plot design. Soil mixture ratio was used as the main-plot factor, and fertiliser regime was used as the sub-plot factor. When significant effects were detected, means were compared using the

Scott-Knott test at $p < 0.05$. When the interaction between soil mixture ratio and fertiliser regime was not significant, only the main effects were interpreted. All analyses were conducted in RStudio version 4.6.0.

RESULTS

Effects of Soil Mixture Ratio (S) and Fertiliser Regime (F) on Morphological Traits and Relative Chlorophyll Content of A-40 and A-46

The effects of fertiliser regime and soil mixture ratio on morphological traits and relative chlorophyll content of A-40 and A-46 are presented in Table 2. Fertiliser regime significantly affected all measured traits in both variants, including leaf length (LL), leaf width (LW), number of leaves per plant (NLP), plant height (PH), SPAD index, and leaf colour index (LC) ($p < 0.001$). In A-40, fertiliser regime significantly affected all measured traits. BF4 showed the highest numerical values for LL (35.55 mm), NLP (12.60), PH (4.58 cm), SPAD index (36.86), and LC (5.82). However, BF4 did not differ significantly from BF3 and GF4 for most of these traits, according to the Scott-Knott test. GF3, GF4, BF3, and BF4 were generally grouped in the highest statistical class for LL, NLP, SPAD index, and LC.

In A-46, BF4 showed the highest numerical values for LL (34.71 mm), NLP (12.62), PH (4.88 cm), SPAD index (37.62), and LC (5.89). However, several higher fertiliser treatments were statistically comparable with BF4. For example, GF3, GF4, BF2, BF3, and BF4 were not significantly different for LL, while GF3, GF4, BF3, and BF4 were grouped together for several other growth traits. BF4 was significantly higher than BF3 and GF4 only for selected traits such as SPAD index.

The soil mixture ratio had weaker effects than the fertiliser regime and significantly affected only selected traits. In A-40, soil mixture ratio significantly affected LL, LW, and LC. S3 produced the highest LL (33.44 mm), while S2 showed the highest LW (6.77 mm) and LC (5.68). In A-46, soil mixture ratio significantly affected LL, PH, and LC. S2 produced the highest LL (32.96 mm), PH (4.35 cm), and LC (5.61).

Effects of Soil Mixture Ratio and Fertiliser Regime on Biomass Traits of A-40 and A-46

Fertiliser regime significantly affected all biomass traits in both A-40 and A-46 ($p < 0.001$; Table 3). In A-40, BF4 produced the highest values for SFW (42.80 g), SDW (8.04 g), RFW (19.68 g), RDW (4.07 g), and RV (16.72 cm^3), while GF3 produced the longest RL (18.37 cm). GF4 also showed relatively high values for SFW (32.35 g), SDW (6.64 g), RFW (17.08 g), RDW (3.78 g), RV (14.08 cm^3), and RL (17.50 cm). Compared with the unfertilised control, fertiliser application clearly improved biomass accumulation in A-40.

Table 2
Main-effect means of morphological traits and SPAD index in A-40 and A-46 under fertiliser regime and soil mixture ratio

		LL (mm)		LW (mm)		NLP		PH (cm)		SPAD (Index)		LC (Index)	
Fertiliser		**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**
F	F0	28.24 c	28.20 c	6.10 c	6.07 d	5.61 c	5.26 c	2.76 c	2.81 c	21.95 d	21.30 e	4.97 c	4.46 c
	GF1	31.01 b	31.42 b	6.59 b	6.48 c	7.27 b	6.51 c	3.44 b	3.77 b	30.05 c	29.94 d	5.45 b	5.51 b
	GF2	32.34 b	31.36 b	6.82 a	6.68 b	8.44 b	8.36 b	3.72 b	4.16 b	32.88 b	32.86 c	5.59 b	5.63 b
	GF3	34.28 a	33.32 a	6.94 a	6.91 a	10.34 a	10.27 a	3.88 a	4.19 b	34.56 a	33.92 b	5.71 a	5.71 a
	GF4	35.18 a	33.98 a	6.87 a	7.07 a	12.15 a	11.62 a	4.14 a	4.67 a	35.52 a	35.51 b	5.75 a	5.86 a
	BF1	31.11 b	30.37 b	6.46 b	6.53 c	6.48 c	6.75 c	3.60 b	4.03 b	30.04 c	29.07 d	5.49 b	5.37 b
	BF2	32.14 b	32.73 a	6.53 b	6.75 b	8.36 b	8.73 b	3.99 a	4.41 a	31.73 b	32.50 c	5.46 b	5.60 b
	BF3	33.12 a	33.34 a	6.78 a	6.91 a	10.61 a	10.48 a	4.34 a	4.70 a	34.93 a	35.51 b	5.74 a	5.67 a
	BF4	35.55 a	34.71 a	6.92 a	7.04 a	12.60 a	12.62 a	4.58 a	4.88 a	36.86 a	37.62 a	5.82 a	5.89 a
	P	***	***	***	***	***	***	***	***	***	***	***	***
		LL (mm)		**LW (mm)**		**NLP**		**PH (cm)**		**SPAD (Index)**		**LC (Index)**	
Soil		**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**
S	S1	31.91 b	30.98 b	6.56 b	6.67 a	8.80 a	8.88 a	3.56 a	3.89 b	32.01 a	32.22 a	5.33 b	5.33 b
	S2	32.3 b	32.96 a	6.77 a	6.68 a	9.19 a	8.87 a	3.99 a	4.35 a	32.38 a	32.12 a	5.68 a	5.61 a
	S3	33.44 a	32.54 a	6.67 a	6.80 a	9.29 a	9.12 a	3.94 a	4.30 a	31.79 a	31.74 a	5.65 a	5.63 a
	P	*	**	*	NS	NS	NS	NS	*	NS	NS	***	***

Note. LL = leaf length; LW = leaf width; SPAD = relative chlorophyll content; NLP = number of leaves per plant; PH = plant height; LC = leaf colour rating. Soil mixture ratio means were averaged across fertiliser regimes, while fertiliser regime means were averaged across soil mixture ratios. Within each column and within the same factor section, means followed by different letters are significantly different at $p \leq 0.05$ according to the Scott-Knott test

Table 3
Main-effect means of biomass traits in A-40 and A-46 under fertiliser regime and soil mixture ratio

		SFW (g)		SDW (g)		RFW (g)		RDW (g)		RV (cm³)		RL (cm)	
Fertiliser		**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**
F	F0	2.48 e	1.79 c	0.67 d	0.51 c	1.36 c	0.80 c	0.43 b	0.23 c	1.97 c	1.03 c	8.47 c	14.50 d
	GF1	13.84 d	12.40 b	2.74 c	3.20 b	5.65 c	5.11 b	1.28 b	1.52 b	5.30 c	4.36 b	12.37 b	17.02 c
	GF2	16.20 d	14.45 b	3.34 c	3.56 b	6.83 c	7.39 b	1.44 b	1.81 b	6.29 c	6.68 b	14.82 a	19.02 c
	GF3	23.69 c	19.67 b	4.73 b	4.42 a	11.21 b	7.94 b	2.22 b	1.71 b	10.17 b	7.47 b	18.37 a	20.59 b
	GF4	32.35 b	28.78 a	6.64 a	5.54 a	17.08 a	13.91 a	3.78 a	2.23 b	14.08 a	11.03 a	17.50 a	22.10 a
	BF1	12.23 d	10.63 b	2.82 c	2.92 b	6.14 c	7.59 b	1.30 b	1.70 b	6.94 c	6.96 b	13.18 b	17.55 c
	BF2	25.50 c	17.60 b	5.69 b	4.55 a	12.12 b	10.39 a	2.46 b	2.19 b	11.18 b	9.29 a	15.02 a	20.42 b
	BF3	35.01 b	29.56 a	7.01 a	5.88 a	17.96 a	12.36 a	3.80 a	2.78 a	15.02 a	11.10 a	15.44 a	22.44 a
	BF4	42.80 a	35.43 a	8.04 a	6.25 a	19.68 a	16.01 a	4.07 a	2.91 a	16.72 a	14.82 a	14.94 a	23.25 a
	P	***	***	***	***	***	***	***	***	***	***	***	***
	SFW (g)	**SDW (g)**	**RFW (g)**	**RDW (g)**	**RV (cm³)**	**RL (cm)**	**SFW (g)**	**SDW (g)**	**RFW (g)**	**RDW (g)**	**RV (cm³)**	**RL (cm)**	**SFW (g)**
Soil		**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**	**A-40**	**A-46**
S	S1	22.85 a	14.98 b	5.06 a	3.52 a	13.04 a	7.76 a	2.57 a	1.66 a	10.80 a	7.29 a	15.61 a	22.10 a
	S2	20.73 a	19.16 a	4.35 a	4.04 a	8.34 b	9.17 a	1.87 a	2.05 a	7.46 b	7.70 a	12.61 b	17.50 c
	S3	24.45 a	22.63 a	4.48 a	4.73 a	11.30 a	10.24 a	2.49 a	1.99 a	10.96 a	9.25 a	15.15 a	19.36 b
	P	NS	**	NS	NS	**	NS	NS	NS	*	NS	*	***

Note. SFW = shoot fresh weight; SDW = shoot dry weight; RFW = root fresh weight; RDW = root dry weight; RV = root volume; RL = root length. Soil mixture ratio means were averaged across fertiliser regimes, while fertiliser regime means were averaged across soil mixture ratios. Within each column and within the same factor section, means followed by different letters are significantly different at $p < 0.05$ according to the Scott-Knott test. Mean comparisons were conducted separately for each variant

In A-46, BF4 produced high biomass rates for SFW (35.43 g), SDW (6.25 g), RFW (16.01 g), RDW (2.91 g), RV (14.82 cm^3) and RL (23.25 cm). BF3 and GF4 resulted in high biomass scores for SFW, RFW, RV and RL. This means that more fertiliser inputs, especially BF4, led to higher shoot and root biomass values in both variants. The soil mixture ratio was weaker than the fertiliser regime and affected only some biomass features. In the A-40s, soil mixture ratios are less significant than fertiliser regimes and mostly affected RFW, RV, and RL. S1 produced the highest RFW (13.04 g) and RL (15.61 cm), and S3 produced the highest RV (10.96 cm^3). In A-46, soil mixture ratio significantly affected SFW and RL. S3 produced a higher SFW (22.63 g), while S1 produced a longer RL (22.10 cm). Overall, the fertiliser regime was the dominant factor affecting biomass accumulation, whereas the soil mixture ratio mainly influenced selected root-related traits.

Agronomic Nitrogen Use Efficiency Based on Total Dry Biomass

Agronomic nitrogen use efficiency (AE_N) was calculated to assess the increase in total dry biomass per unit of applied nitrogen (Table 4). AE_N was calculated from treatment-mean total dry biomass to compare biomass gain per unit of nitrogen applied among fertiliser regimes. Values for S1, S2, and S3 are also presented to show the fertiliser responses under different soil mixture ratios.

Table 4
Agronomic nitrogen use efficiency based on total dry biomass of A-40 and A-46 under different NPK fertiliser regimes

Fertiliser	Total N Applied	S1 AE_N (g g^{-1})		S2 AE_N (g g^{-1})		S3 AE_N (g g^{-1})		Main Effect AE_N (g g^{-1})	
		A-40	A-46	A-40	A-46	A-40	A-46	A-40	A-46
GF1	0.50	44.56	66.43	97.50	89.41	30.57	81.22	57.54	79.02
GF2	0.76	43.46	61.14	67.63	61.14	34.67	61.44	48.55	61.24
GF3	1.01	73.73	47.55	49.15	42.66	50.75	70.13	57.84	53.45
GF4	1.50	67.23	38.86	66.93	44.46	51.65	57.34	61.94	46.85
BF1	0.50	54.25	48.85	59.04	57.24	67.63	127.27	60.34	77.82
BF2	0.75	86.71	78.32	64.44	88.71	130.07	73.63	93.71	80.22
BF3	1.00	124.48	55.24	70.53	100.10	96.30	82.62	97.10	79.32
BF4	1.50	90.61	51.05	60.74	58.04	68.93	59.54	73.43	56.24

Note. AE_N = agronomic nitrogen use efficiency based on total dry biomass; S1 = 100:0 (sand: topsoil); S2 = 0:100 (sand: topsoil); S3 = 70:30 (sand: topsoil). GF = NPK 15-15-15 + 2S; BF = NPK 12-12-17 + TE. Numbers 1-4 indicate 0.5×, 0.75×, 1.0×, and 1.5× of the recommended fertiliser rate, respectively. AE_N was calculated as the increase in total dry biomass per unit of nitrogen applied, relative to the corresponding unfertilised control (F0). Values are expressed as g total dry biomass increase per g N applied. F0 is not shown because AE_N cannot be calculated for unfertilised control. Values for individual soil mixture ratio-fertiliser combinations are presented for descriptive purposes only

In A-40, AE_N values varied among fertiliser regimes. Based on the fertiliser main effect means, BF3 showed the highest AE_N (97.10 g total dry biomass increase per g N applied), followed by BF2 (93.71) and BF4 (73.43). Among the NPK 15-15-15 + 2S treatments, GF4 showed the highest AE_N (61.94), followed by GF3 (57.84) and GF1 (57.54). Although BF4 produced the greatest total dry biomass, its AE_N was lower than that of BF3, indicating that the additional fertiliser input resulted in a smaller biomass gain per unit of N applied. In A-46, BF2 showed the highest numerical AE_N (80.22), followed closely by BF3 (79.32), GF1 (79.02), and BF1 (77.82). By contrast, BF4 showed a lower AE_N value (56.24), while GF4 had the lowest AE_N among the fertilised treatments (46.85).

Relationships of SPAD Index with Leaf Colour, Morphological Traits

Correlation analysis showed moderate-to-strong positive correlations among the morphological traits in both A-40 and A-46 (Figure 2). In A-40 (Figure 2a), SPAD index was strongly correlated with leaf length (LL; r = 0.88), leaf width (LW; r = 0.88), number of leaves per plant (NLP; r = 0.87), plant height (PH; r = 0.87), and leaf colour (LC; r = 0.75). In A-46 (Figure 2b), the correlations among morphological traits were generally stronger than those in A-40. SPAD index was positively correlated with LL (r = 0.85), LW (r = 0.90), NLP (r = 0.91), PH (r = 0.89), and LC (r = 0.88).

Relationships of SPAD Index with Biomass Traits

Pearson correlation analysis was conducted to evaluate the relationships between SPAD index and biomass traits, including shoot fresh weight (SFW), shoot dry weight (SDW), root fresh weight (RFW), root dry weight (RDW), root volume (RV), and root length (RL) in A-40 and A-46 (Figure 3). In A-40, SPAD index was positively correlated with all biomass traits, with correlation coefficients ranging from r = 0.67 to 0.82. The strongest correlations were observed for SDW (r = 0.82) and SFW (r = 0.81), so high SPAD values generally lead to larger shoot biomass. In A-46, SPAD showed even stronger correlations with biomass traits, ranging from r = 0.74 to 0.89, with the highest correlation observed for SDW (r = 0.89) and SFW (r = 0.85).

DISCUSSION

The fertiliser regime had a significant effect on morphological and biomass-related traits for both *A. compressus* mutant variants (A-40 and A-46). The number of leaves per plant (NLP) responded strongly to fertilisation, increasing by as much as 124.6% in A-40 and 139.9% in A-46 relative to the unfertilised controls. The results indicate that proper nutrient supply can improve tillering, canopy development and overall morpho-physiological growth of turfgrass (Kussow et al., 2012; Shaddox et al., 2017).

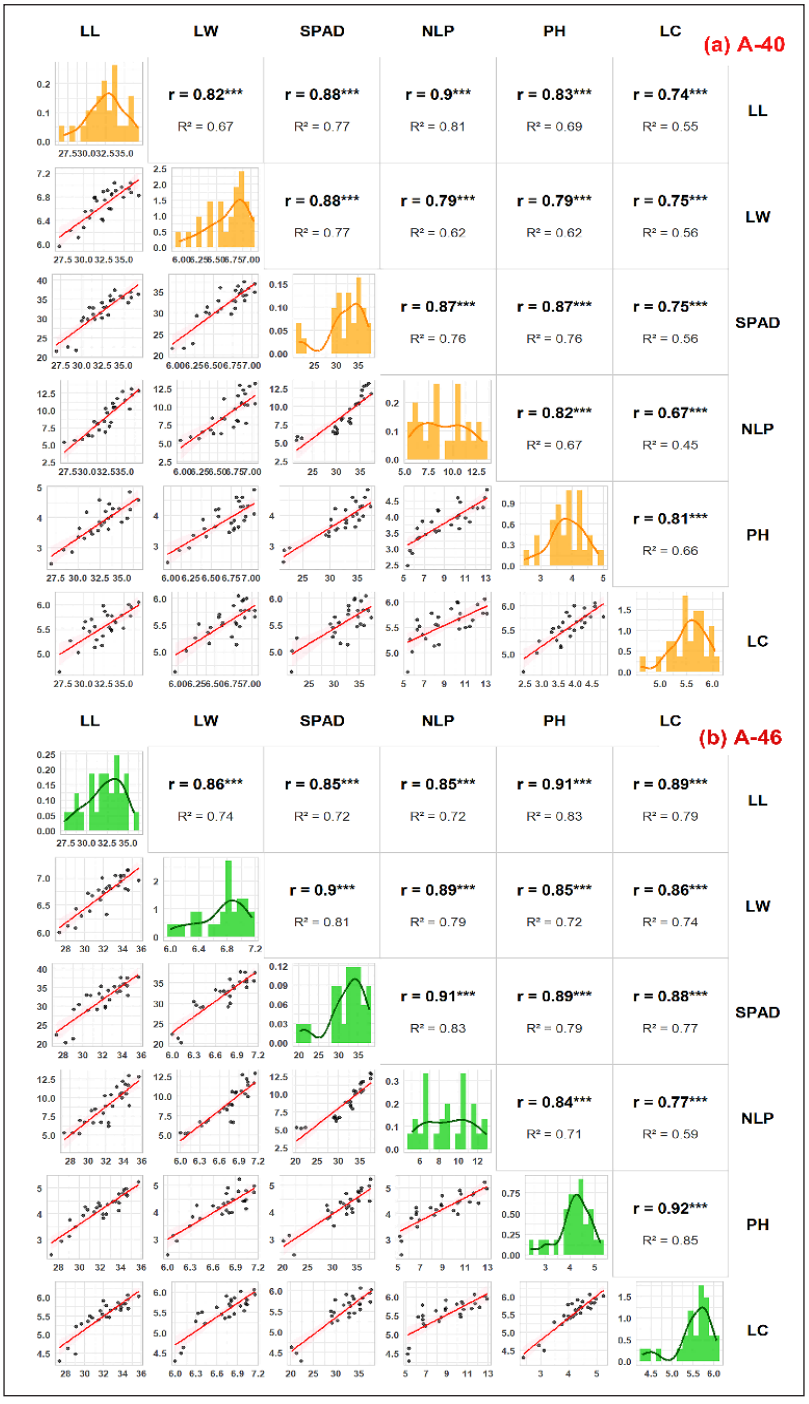

Figure 2. Relationships among SPAD index, leaf colour, and morphological traits in (a) A-40 and (b) A-46
Note. Asterisks indicate significance levels ($p < 0.05$, $p < 0.01$, $p < 0.001$). r = Pearson correlation coefficient; R^2 = coefficient of determination. LL - leaf length, LW - leaf width, SPAD - relative chlorophyll content, NLP - number of leaves per plant, PH - plant height, LC - leaf colour

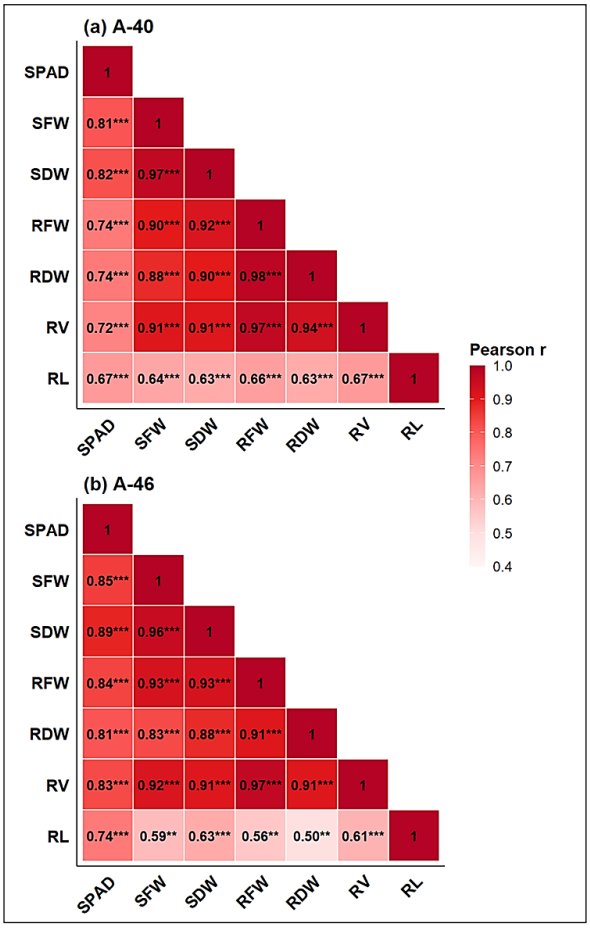

Figure 3. Relationships between SPAD index and biomass traits in (a) A-40 and (b) A-46
Note. Asterisks indicate significance levels ($p < 0.05$, $p < 0.01$, $p < 0.001$). r = Pearson correlation coefficient; R^2 = coefficient of determination. SFW - shoot fresh weight, SDW - shoot dry weight, RFW - root fresh weight, RDW - root dry weight, RV - root volume, RL - root length, SPAD - relative chlorophyll content

Both NPK fertiliser regimes improved morphological traits, but their effects varied among traits. NPK (15-15-15 + 2S), as a balanced NPK formulation, supported vegetative growth, while NPK (12-12-17 + TE) generally produced high values for SPAD index, leaf colour, and several growth traits.

In contrast, the NPK (12-12-17 + TE) fertiliser group, characterised by higher potassium and trace elements, produced greater improvements in SPAD and leaf colour, consistent with the role of potassium in chlorophyll synthesis, stomatal regulation, and stress tolerance (Johnson et al., 2022). The trace elements in NPK 12-12-17 + TE may have contributed to the greater biomass production, as micronutrients such as Fe, Mn, Zn, and Cu are involved in chlorophyll formation, enzyme activity, and photosynthesis.

Sulfur supplied by NPK 15-15-15 + 2S may support the synthesis of sulfur-containing amino acids and proteins and thereby contribute to plant metabolic activity and biomass formation. Since tissue nutrient concentrations were not measured, however, these explanations should be interpreted with caution. Compared with F0, SPAD index increased by up to 67.9% in A-40 and 76.6% in A-46 under BF4. SPAD measurements are commonly used as rapid indicators of relative chlorophyll status and leaf greenness. The availability of nitrogen is intimately associated with leaf chlorophyll since it is a component of chlorophyll and photosynthetic proteins (Fathi, 2022; Qi et al., 2025). Many studies showed that maintaining a chlorophyll content under stress is correlated with an increased tolerance to heat, drought or nutrient limitation (Poudyal et al., 2024; Pratap et al., 2025).

Although fertiliser was the main part of growth responses, soil mixture ratio also helped some traits (Chou et al., 2024; Ofori et al., 2024). S3 generally had higher growth than S1 or S2, probably due to better water retention, aeration and nutrient availability in topsoil-mixtures (see 70:30 sand: topsoil) (Brown et al., 1985; McCoy, 1998; Zhang & Han, 2019). The two mutant variants responded differently to soil mixing ratios, which indicates differences between mutants of the same species regarding their sensitivity to culture medium conditions (Huang et al., 2021). The absence of significant soil × fertiliser (S × F) interactions across all traits indicates that the relative responses to fertiliser were generally stable across soil mixture ratios. This further supports interpreting AE_N mainly based on the fertiliser main effects, while the values for S1, S2, and S3 show that the fertiliser response was generally consistent across the different soil mixture ratios. However, soil physical properties are also important for turfgrass establishment. Therefore, fertilisation should be considered together with soil substrate selection in tropical turfgrass systems.

Biomass accumulation in turfgrass was influenced by soil mixture ratio and fertiliser regime. High fertiliser rates resulted in substantial increases in shoot and root biomass. Moreover, S1 generally produced longer roots than S2 and S3, especially in A-46. A-46 had longer roots in the sandy medium. One possible reason is that the lower water and nutrient retention in this substrate encouraged greater root extension. Since root anatomy and nutrient uptake were not examined, the reason for this response remains unclear. Root elongation may have been favoured in the sandy medium, which offers little mechanical resistance to penetration but loses nutrients readily through leaching; longer roots would then allow a larger volume of substrate to be explored for nutrient uptake (Lynch, 2019). Of the fertiliser treatments, NPK 12-12-17 + TE and BF4, in particular, generally gave higher shoot and root fresh weights, along with greater root dry weight and root volume, indicating stronger stimulation of biomass accumulation. Even so, a larger plant does not by itself indicate that the fertiliser was used more efficiently. Total biomass accumulation

alone did not fully reflect fertiliser-use efficiency. In A-40, BF4 produced the highest total biomass, but AE_N was highest under BF3, showing a greater dry biomass gain per unit of nitrogen applied. In A-46, BF2 and BF3 showed the highest numerical AE_N values. These results indicate that the highest fertiliser rate did not necessarily provide the greatest biomass return per unit of nitrogen input (Springer, 2021). Although BF4 generally produced higher total dry biomass, its lower AE_N compared with BF2 or BF3 indicates that biomass gain per unit of nitrogen declined at the highest fertiliser rate. This suggests that moderate fertiliser rates may offer a better balance between turfgrass growth and nitrogen input than the highest rate (Bastidas et al., 2024). Additional nutrient input does not always lead to proportional increases in biomass. This is particularly relevant for turfgrass management, where over-fertilisation can raise costs and increase the risk of nutrient losses without providing clear benefits to growth or turf quality.

Besides soil mixture ratio and fertiliser usage, there were differences in the growth of the two variants. Growth parameters were strongly correlated between A-40 and A-46. In particular, A-46 was stronger than A-40 in leaf colour, SPAD, and biomass traits. Therefore, the relationships between SPAD and biomass traits were generally stronger in A-46 than in A-40, suggesting that SPAD may be a useful non-destructive indicator of biomass variation in A-46. Across treatments, SPAD readings closely tracked biomass, and the relationship was strongest for shoot weight: plants with greener foliage were, by and large, those that had accumulated more shoot material. Since reading takes seconds and requires no harvest, SPAD appears well suited to routine monitoring of sward growth. These results may partly explain its better potential adaptability. A clear plateau effect was observed in both fertiliser groups, beyond BF3 in the NPK (12-12-17 + TE) fertiliser group and GF2-GF3 in the NPK (15-15-15 + 2S) group, with only marginal improvements at higher levels (Supplementary Figures S1-S12). This pattern may reflect a diminishing marginal response to fertiliser input rather than a continued proportional improvement in turfgrass performance. Further fertilisation beyond the point of low marginal biomass returns may increase the risk of nutrient leaching without clear additional gains in turf functional quality (Zhu et al., 2024). Others show a similar pattern: once nutrient supply exceeds what the plant can use, each further increment of fertiliser brings progressively smaller gains in biomass (Li et al., 2023). This bears directly on input-aware fertilisation of turfgrass, where the goal is to match application to demand rather than to maximise growth. It also echoes the decline in nitrogen use efficiency documented across modern agriculture (Zhang et al., 2015). The lower AE_N at the highest fertiliser rate shows that more fertiliser does not always lead to better nutrient efficiency. Further investigation into fertiliser timing, application frequency, and soil mixture management could provide more refined turf management strategies.

CONCLUSION

This study evaluated the responses of two *A. compressus* variants, A-40 and A-46, to three soil mixture ratios and graded NPK fertiliser regimes. The results showed that fertiliser regime was the main factor affecting growth, SPAD, leaf colour, and biomass. Although BF4 produced the highest biomass, the highest agronomic nitrogen use efficiency was found under BF3 in A-40 and BF2-BF3 in A-46. SPAD index and leaf colour were positively related to morphological and biomass traits. However, this study was conducted under tray-based conditions, and soil nutrient dynamics and plant tissue nutrient concentrations were not directly measured. Future studies should validate these responses under field conditions and include soil and tissue nutrient analyses.

ACKNOWLEDGEMENT

We are grateful to Satiri Sdn. Bhd. and the UPM Industrial Research Grant (Grant No. 6300403-10201) for providing financial support to conduct this research. The authors also acknowledge the University Driven Research Program (UDRP) under the Research Framework: Technology Advancement for Economic Growth and the Research Programme: Plantation Crops - Oil Palm, Rubber, Cocoa, Kenaf (upstream and downstream), Institute of Plantation Studies, Universiti Putra Malaysia. Additional support for publication fees was provided by the GLTU Doctoral Training Research Fund (Grant No. CZ6125002), and Capacity Building Project for Science Communication on Lijiang Ecological Protection and Sustainable Landscape Utilization (Grant No. FN2600640405).

REFERENCES

Alif, A. A. A. H., & Amira, H. N. (2023). Effect of NPK green mix with different type of manure on spinach growth and yield. *IOP Conference Series: Earth and Environmental Science*, *1182*, Article 012041. https://doi.org/10.1088/1755-1315/1182/1/012041

Azuddin, N. F., Azmy, M. S. M. N., & Zakaria, L. (2023). Molecular identification of endophytic fungi in lawn grass (*Axonopus compressus*) and their pathogenic ability. *Scientific Reports*, *13*, Article 4239. https://doi.org/10.1038/s41598-023-31291-7

Bastidas, M., Vázquez, E., Villegas, D. M., Rao, I. M., Gutierrez, J. F., Vivas-Quila, N. J., Amado, M., Berdugo, C., & Arango, J. (2024). Optimizing nitrogen use efficiency of six forage grasses to reduce nitrogen loss from intensification of tropical pastures. *Agriculture, Ecosystems & Environment*, *367*, Article 108970. https://doi.org/10.1016/j.agee.2024.108970

Bhatia, A., Cowan, N. J., Drewer, J., Tomer, R., Kumar, V., Sharma, S., Paul, A., Jain, N., Kumar, S., Jha, G., Singh, R., Prasanna, R., Ramakrishnan, B., Bandyopadhyay, S. K., Kumar, D., Sutton, M. A., & Pathak, H. (2023). The impact of different fertiliser management options and cultivars on nitrogen use efficiency and yield for rice cropping in the Indo-Gangetic Plain: Two seasons of methane, nitrous oxide and ammonia emissions. *Agriculture, Ecosystems & Environment*, *355*, Article 108593. https://doi.org/10.1016/j.agee.2023.108593

Brown, K. W., Evans, G. B., & Thomas, J. C. (1985). Increased soil water retention by mixing horizons of shallow sandy soils. *Soil Science*, *139*(2), 118-121. https://doi.org/10.1097/00010694-198502000-00004

Carlson, M. G., Gaussoin, R. E., & Puntel, L. A. (2022). A review of precision management for golf course turfgrass. *Crop, Forage & Turfgrass Management*, *8*(2), Article e20183. https://doi.org/10.1002/cft2.20183

Chou, M.-Y., Pavlou, D., Rice, P. J., Spokas, K. A., Soldat, D. J., & Koch, P. L. (2024). Microbial diversity and soil health parameters associated with turfgrass landscapes. *Applied Soil Ecology*, *196*, Article 105311. https://doi.org/10.1016/j.apsoil.2024.105311

Easton, Z. M., & Petrovic, A. M. (2004). Fertiliser source effect on ground and surface water quality in drainage from turfgrass. *Journal of Environmental Quality*, *33*(2), 645-655. https://doi.org/10.2134/jeq2004.6450

Fathi, A. (2022). Role of nitrogen (N) in plant growth, photosynthesis pigments, and N use efficiency: A review. *Agrisost*, *28*, 1-8. https://doi.org/10.5281/zenodo.7143588

Głąb, T., Szewczyk, W., Gondek, K., Mierzwa-Hersztek, M., Palmowska, J., & Nęcka, K. (2020). Optimization of turfgrass fertigation rate and frequency. *Agricultural Water Management*, *234*, Article 106107. https://doi.org/10.1016/j.agwat.2020.106107

Hamarashid, N. H., Othman, M. A., & Hussain, M.-A. H. (2010). Effects of soil texture on chemical compositions, microbial populations and carbon mineralization in soil. *Egyptian Journal of Experimental Biology (Botany)*, *6*(1), 59-64.

He, L., Teng, L., Tang, X., Long, W., Wang, Z., Wu, Y., & Liao, L. (2021). Agro-morphological and metabolomics analysis of low nitrogen stress response in *Axonopus compressus*. *AoB PLANTS*, *13*(4), Article plab022. https://doi.org/10.1093/aobpla/plab022

Huang, X., Jang, S., Kim, B., Piao, Z., Redona, E., & Koh, H.-J. (2021). Evaluating genotype × environment interactions of yield traits and adaptability in rice cultivars grown under temperate, subtropical and tropical environments. *Agriculture*, *11*(6), Article 558. https://doi.org/10.3390/agriculture11060558

Islam, M. R., Haque, S., Akter, N., & Karim, M. (2014). Leaf chlorophyll dynamics in wheat based on SPAD meter reading and its relationship with grain yield. *Scientia Agriculturae*, *8*(1), 13-18. https://doi.org/10.15192/PSCP.SA.2014.4.1.1318

Johnson, R., Vishwakarma, K., Hossen, M. S., Kumar, V., Shackira, A. M., Puthur, J. T., Abdi, G., Sarraf, M., & Hasanuzzaman, M. (2022). Potassium in plants: Growth regulation, signaling, and environmental stress tolerance. *Plant Physiology and Biochemistry*, *172*, 56-69. https://doi.org/10.1016/j.plaphy.2022.01.001

Kopp, K. L., & Guillard, K. (2002). Relationship of turfgrass growth and quality to soil nitrate desorbed from anion exchange membranes. *Crop Science*, *42*(4), 1232-1240. https://doi.org/10.2135/cropsci2002.1232

Kussow, W. R., Soldat, D. J., Kreuser, W. C., & Houlihan, S. M. (2012). Evidence, regulation, and consequences of nitrogen-driven nutrient demand by turfgrass. *ISRN Agronomy*, *2012*(1), Article 359284. https://doi.org/10.5402/2012/359284

Li, B., Ma, X., Zhao, B., Wang, L., & Ata-Ul-Karim, S. T. (2023). In-season assessment of agronomic nitrogen use efficiency and its components in winter wheat using critical nitrogen dilution curve. *Frontiers in Plant Science*, *14*, Article 1128799. https://doi.org/10.3389/fpls.2023.1128799

Li, H., Zhang, Y., Sun, Y., Liu, P., Zhang, Q., Wang, X., Wang, R., & Li, J. (2023). Long-term effects of optimized fertilisation, tillage and crop rotation on soil fertility, crop yield and economic profit on the Loess Plateau. *European Journal of Agronomy*, *143*, Article 126731. https://doi.org/10.1016/j.eja.2022.126731

Lynch, J. P. (2019). Root phenotypes for improved nutrient capture: An underexploited opportunity for global agriculture. *New Phytologist*, *223*(2), 548-564. https://doi.org/10.1111/nph.15738

McCoy, E. L. (1998). Sand and organic amendment influences on soil physical properties related to turf establishment. *Agronomy Journal*, *90*(3), 411-419. https://doi.org/10.2134/agronj1998.00021962009000030016x

Ofori, B., Habteselassie, M., & Martinez-Espinoza, A. (2024). Effect of turfgrass care products on soil biological health, disease suppression, and turfgrass quality. *Applied Soil Ecology*, *201*, Article 105499. https://doi.org/10.1016/j.apsoil.2024.105499

Petrovic, A. M., Soldat, D. J., Gruttadaurio, J., & Barlow, J. (2005). Turfgrass growth and quality related to soil and tissue nutrient content. *International Turfgrass Society Research Journal*, *10*, 989-997.

Poudyal, D., Krishna Joshi, B., & Chandra Dahal, K. (2024). Insights into the responses of Akabare chili landraces to drought, heat, and their combined stress during pre-flowering and fruiting stages. *Heliyon*, *10*(16), Article e36239. https://doi.org/10.1016/j.heliyon.2024.e36239

Pratap, A., Taylor, N. L., Pal, M., Chinnusamy, V., & Siddique, K. H. M. (2025). Heat tolerance mechanisms in bread wheat: Insights from flag leaves and spike tissues. *Plant Stress*, *16*, Article 100876. https://doi.org/10.1016/j.stress.2025.100876

Qi, Z., Xu, C., Tang, R., Zhang, Q., Sun, W., Guan, C., Wang, Y., Zhang, M., Ding, J., Zhang, Y., Yang, H., Yang, Y., Liu, X., Zhang, Z., & Ling, F. (2025). Response of photosynthesis and chlorophyll fluorescence to nitrogen changes in rice with different nitrogen use efficiencies. *Plants*, *14*(10), Article 1465. https://doi.org/10.3390/plants14101465

Roberson, T. L., Badzmierowski, M. J., Stewart, R. D., Ervin, E. H., Askew, S. D., & McCall, D. S. (2021). Improving soil moisture assessment of turfgrass systems utilizing field radiometry. *Agronomy*, *11*(10), Article 1960. https://doi.org/10.3390/agronomy11101960

Shaddox, T. W., Ryan, C. D., & Tang, K. (2017). Reference ranges: A novel interpretation of turfgrass nutrient values. *Agricultural & Environmental Letters*, *2*(1), Article 160046. https://doi.org/10.2134/ael2016.12.0046

Shaddox, T. W., & Unruh, J. B. (2021). Determining nitrogen fertiliser cost using turfgrass response. *HortTechnology*, *31*(4), 470-478. https://doi.org/10.21273/HORTTECH04837-21

Shivashankar, K., Potdar, M. P., Gawdiya, S., Golshetti, A., Kanade, A. K., Balol, G., Biradar, D. P., Math, K. K., Al-Ansari, N., El-Hendawy, S., Mattar, M. A., & Salem, A. (2025). SPAD dynamics in maize crop with precision nitrogen management under rain-fed and irrigated conditions. *Scientific Reports*, *15*, Article 22842. https://doi.org/10.1038/s41598-025-05255-y

Sim, C. C., Zaharah, A. R., Tan, M. S., & Goh, K. J. (2015). Rapid determination of leaf chlorophyll concentration, photosynthetic activity and NK concentration of *Elaeis guineensis* via correlated SPAD-502 chlorophyll index. *Asian Journal of Agricultural Research*, *9*(3), 132-138. https://doi.org/10.3923/ajar.2015.132.138

Springer, R., Eudoxie, G., & Gouveia, G. (2014). Comparative evaluation of common savannah grass on a range of soils subjected to different stresses II: Root zone physical condition. *Agronomy*, *4*(1), 124-143. https://doi.org/10.3390/agronomy4010124

Springer, T. L. (2021). Effect of nitrogen fertilisation on biomass yield of sand bluestem (*Andropogon hallii* Hack.). *BioEnergy Research*, *14*, 1118-1125. https://doi.org/10.1007/s12155-020-10220-w

Wahid, M. K., Jumaidin, R., Suan, M. S. M., & Md Yusof, F. A. (2023). Characterisation of *Axonopus compressus* fibre through chemical composition, thermogravimetric behaviour, and moisture content evaluation. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *110*(1), 172-181. https://doi.org/10.37934/arfmts.110.1.172181

Yuan, Z., Cao, Q., Zhang, K., Ata-Ul-Karim, S. T., Tian, Y., Zhu, Y., Cao, W., & Liu, X. (2016). Optimal leaf positions for SPAD meter measurement in rice. *Frontiers in Plant Science*, *7*, Article 719. https://doi.org/10.3389/fpls.2016.00719

Zhang, L., & Han, J. (2019). Improving water retention capacity of an aeolian sandy soil with feldspathic sandstone. *Scientific Reports*, *9*, Article 14719. https://doi.org/10.1038/s41598-019-51257-y

Zhang, X., Davidson, E. A., Mauzerall, D. L., Searchinger, T. D., Dumas, P., & Shen, Y. (2015). Managing nitrogen for sustainable development. *Nature*, *528*, 51-59. https://doi.org/10.1038/nature15743

Zhu, L., Sun, H., Liu, L., Zhang, K., Zhang, Y., Li, A., Bai, Z., Wang, G., Liu, X., Dong, H., & Li, C. (2025). Optimizing crop yields while minimizing environmental impact through deep placement of nitrogen fertiliser. *Journal of Integrative Agriculture*, *24*(1), 36-60. https://doi.org/10.1016/j.jia.2024.05.012