CHILEAN JOURNAL of AGRICULTURAL RESEARCH

RESEARCH ARTICLE

Growth, yield and potassium dynamics of konjac (*Amorphophallus muelleri* Blume) under different shading and potassium fertilization rates

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Received: 11 November 2025; Accepted: 25 February 2026, doi:10.4067/S0718-58392026000300392

ABSTRACT

Konjac (*Amorphophallus muelleri* Blume) is a tuberous species that thrives in Malaysian forests and has substantial commercial potential. Despite its importance, agronomic practices that suited with local climate is still scarce. Optimizing key agronomic practices such as shade and K rates require a clear understanding of how they affect plant growth and nutrient dynamics, and how these effects, in turn, influence yield. A field experiment was conducted and treatments of four K rates – 0 (T1), 75 (T2), 150 (T3), 225 (T4) kg ha^{-1} were nested in three shading rates – 0%, 50%, 70%. Under each shading, each K rate was arranged in a randomized complete block design (RCBD) with four replicates. Regardless of K rates, plants under 70% shading had enhanced growth (leaflet area, petiole diameter), 33.1% more rapid K uptake and 27.9% higher corm yield ($P \leq 0.01$; $\alpha = 0.05$), attributed to 15.71% higher photosynthesis rates compared to plants under 50% shading. For nested effects, under 70% shading, T3 was optimum since K uptake and growth was delayed in T4 plants and the corm yield showed nonsignificant difference to T3. Under 50% shading, yield in T4 plants were significantly ($P \leq 0.01$; $\alpha = 0.05$) higher (46.4%) compared to T3 plants, demonstrating that under less favourable shading, higher K rate (225 kg ha^{-1}) is needed to increase the yield. Soil K content across growth stages follows quadratic function and the optimum time for K fertilization which can enhance its uptake efficiency under the recommended 70% shading rate is 9-10 wk after planting.

Key words: Dry matter, fertilizer, konjac, potassium rates, potassium uptake, shading.

INTRODUCTION

The genus *Amorphophallus*, a member of the Araceae family, comprises a group of perennial herbs with over 200 described species. The genus exhibits a paleotropical distribution, with its center of diversity in Southeast Asia, though species are also found in Africa, Madagascar, and Australasia (Henriquez et al., 2014). Each plant grows from a subterranean corm, which is a solid underground storage organ. From this corm, a single, often large and highly dissected leaf emerges during the vegetative period, functioning to photosynthesize and replenish the corm's reserves (Yang et al., 2021). The corms of several species are rich in glucomannan, a soluble dietary fiber with high water-absorbing capacity and gel-forming properties. Glucomannan is valued for its physiological benefits including improved glycaemic control, cholesterol reduction, bowel regulation and weight management (Zhang et al., 2023). Its high viscosity also makes it an important industrial ingredient, widely applied in functional foods, gluten-free products, and nutraceutical formulations, thereby combining technological utility with health-promoting functions (Zhang et al., 2023).

Several *Amorphophallus* species hold significant economic and cultural value, particularly in Asia. Economically important species within the genus include *A. konjac, A. muelleri*, and *A. paeoniifolius*. The species *A. muelleri* Blume has been used in the industry and it was reported that this species recorded the highest glucomannan content (64% dry weight) compared to other konjac species (Rizoputra et al., 2024). This tuberous species thrives in Malaysian forests and has significant potential for commercialization. However, reports on agronomic practices that suited with local climate is still lacking. To meet the demand of downstream industries, it is essential to optimize agronomic practices for cost-effectively cultivating this species locally while achieving high yields.

One of the key agronomic practices is shading rate. Being originated from tropical forest ecosystem, *Amorphophallus* species are sciophytes which adapted to low-light environments (Hetterscheid and Ittenbach, 1996). Studies on *A. muelleri* in Indonesia show that 50% shading promotes taller petioles and larger leaf area index, enhancing light capture efficiency without causing etiolation (Santosa et al., 2018). Similarly, research on *A. konjac* in China demonstrates that 40% shading results in optimal plant height and leaf expansion, while full sunlight conditions lead to stunted growth and reduced leaf size (Liu et al., 2020). To date, no studies have investigated the effects of shading levels on *Amorphophallus* species in Malaysia. This knowledge gap is significant because plant responses to shading are highly dependent on local climatic conditions, including solar radiation intensity, temperature, and humidity regimes, which differ substantially between Malaysia, Indonesia, and China. As a result, shading levels identified as optimal in other countries may not necessarily produce comparable outcomes under Malaysian growing conditions.

Potassium is one of the three primary macronutrients essential for plant growth, and it plays a critical role in fundamental physiological processes such as enzyme activation, photosynthesis, and the transport of sugars, which directly influences crop yield and quality (Zörb et al., 2014). Across tuberous crops, K has repeatedly been shown to enhance tuber initiation and bulking, increase yield, and improve marketable quality for example in cassava (Chua et al., 2020), sweet potato (Liu et al., 2024), yam (Chen et al., 2023) and konjac (Douglas, 2005).

The global production and supply of K fertilizer are geographically concentrated, with a small number of countries and corporate entities controlling the majority of the world's production capacity and proven reserves, which significantly influences global distribution, trade flows, and market stability. The demand for K fertilizers has seen a consistent and substantial increase over the past several decades, a trend driven primarily by the need to intensify agricultural production to feed a growing global population and the increasing cultivation of high-value, K-demanding crops in regions where soil K reserves are naturally low (Chen et al., 2024). This rising demand emphasizes the critical importance of using K fertilizers sustainably, as the mining of potash is a non-renewable process and inefficient application can lead to economic losses and environmental consequences such as nutrient leaching and soil salinization.

Clarifying the patterns of K uptake and soil reserve depletion under different growing conditions would provide a scientific basis for optimizing fertilization strategies. It is therefore crucial to elucidate the interplay among shading level, K application, and soil K dynamics in *A. muelleri*. In view of that, this study was conducted with the objective of determining the optimum shading level, K rate, and fertilization timing in seed-propagated *A. muelleri* by evaluating growth responses, K uptake, soil nutrient dynamics, and yield performance.

MATERIALS AND METHODS

Experimental site, land preparation, planting distance, and irrigation

The experimental plot was located at Faculty of Agriculture, Universiti Putra Malaysia (UPM). Soil type was the Munchong-Seremban series (Haplic Ferralsol, FAO classification). Prior to planting, random soil sampling of the plot was collected and analyzed at the Soil Physics Laboratory, Department of Land Management, Faculty of Agriculture, UPM. Physical-chemical properties are presented in Table 1. The plot was treated with 1.5 t ha^{-1} ground Mg limestone (GML; 15% MgO, 40% CaO), 10 d before planting which had increased the soil pH from 5.19 to 6.0. The liming was done simultaneously with the application of processed chicken manure at 5 t ha^{-1}. Planting beds with 35 ± 5 × 105 ± 5 × 175 ± 5 cm (height × width × length) were then constructed for each experimental unit and covered using UV polyethylene mulch. On each planting bed, the plants were arranged in three rows with a 30 cm distance between them. The distance between plants in the same row was 15 cm whilst the diameter of the planting point was 10 cm. The plants were irrigated using a drip irrigation system.

Table 1. Selected physicochemical properties of soil before planting (mean ± SE; *n* = 5).

Soil properties	Values
Sand, %	46.50 ± 3.20
Clay, %	45.84 ± 2.30
Silt, %	7.71 ± 0.75
Bulk density, g cm^{-3}	1.54 ± 0.23
Porosity, %	42.20 ± 4.70
Soil pH	5.10 ± 0.50
EC, µS cm^{-1}	17.84 ± 3.20
Total N, %	0.20 ± 0.03
Total C, %	1.42 ± 0.24
Available P, mg kg^{-1}	4.57 ± 2.43
K Exchangeable cations, $cmol_c$ kg^{-1}	0.47 ± 0.22
Ca Exchangeable cations, $cmol_c$ kg^{-1}	1.63 ± 0.36
Mg Exchangeable cations, $cmol_c$ kg^{-1}	0.37 ± 0.22
Cation exchange capacity, $cmol_c$ kg^{-1}	7.82 ± 2.19

Planting materials

Amorphophallus muelleri Blume seeds were received from Ladang Konjak Ltd. (Negeri, Sembilan, Malaysia) in October 2023. The seeds were treated with fungicide (mancozeb 80% w/w) and kept in an ambient room for 3 wk for germination. The pre-germinated seeds with plumule length of 1.0 ± 0.3 cm were sown directly into the soil at about 2-4 cm depth.

Treatments and experimental design

The plants grew under three different shading rates (0% – direct sunlight, 50%, and 70%). After 7 d of planting, the plants at each shading rate were given four different rates of muriate of potash (60% K_2O) manually *viz.* – 0, 0.75, 1.50, and 2.25 g $plant^{-1}$ respectively, equivalent to 0, 75, 150, and 225 kg ha^{-1} K_2O under a planting density of 166 600 plants ha^{-1}. The experimental design used was the nested randomized complete block design (RCBD), with K rate nested in shading rate, replicated four times.

Nitrogen and phosphorus fertilizers

Nitrogen and P fertilizers were kept constant across all treatments. Ammonium sulfate (21% N w/w and 24% S w/w) at a rate of 50 kg ha^{-1} was used as the source of N, at 7 d of planting while rock phosphate (34% P_2O_5) at 200 kg ha^{-1} was used as the source of P during planting. Both fertilizers were applied within the canopy of the plants.

Determination of soil and foliar K concentration

For soil K concentration, exchangeable base (K^+) was determined at pre-planting, 16 wk after planting (WAP) and post-harvest stage (34 WAP) by the replacement of exchangeable cations with ammonium acetate (1 N NH_4OAc) adjusted to pH 7.0 (Thomas, 1982). The exchangeable base (K^+) in the first leachate was determined by atomic absorption spectrophotometer (AAS) (Model 3110, PerkinElmer, Waltham, Massachusetts, USA) and expressed in $cmol_c$ kg^{-1} soil. For foliar concentration, leaflets were sampled at random from each treatment at three different stages of growth namely 9, 16, 23 WAP. Following drying and grinding, the samples were digested using H_2SO_4 and H_2O_2. The digested samples were then analyzed for K concentration using the AAS.

Determination of growth performance

Destructive sampling was conducted at every 5 wk interval (5, 10, 15, 20 WAP) where data on growth, DM content and corms development were collected. Measurement of petiole height was taken from the surface of the soil to the midrib branching by using a measuring tape while petiole diameter was measured at the lowest part of the petiole using electronic digital caliper (SCM DIGV-6, Mitutoyo, Kawasaki, Japan). During destructive sampling, the whole plants were then separated into leaflets, petiole, root and corm (if visible). The dry weight of each part was determined after 72 h at 75 °C in a drying oven. Plant DM was determined by combining all the dry weights of the plant parts and expressed in g plant^{-1}. Leaflet areas were measured and recorded as total leaflet area per plant using automatic leaf area meter (LI-300, LI-COR Biosciences, Lincoln, Nebraska, USA).

Determination of photosynthesis and stomatal conductance rate

At 10 WAP, net photosynthesis rate (A) and stomatal conductance (g_s) were measured on the selected fully expanded leaves by using a portable close photosynthesis measurement system (infra-red gas analyzer LI-6400, LI-COR Biosciences). The measurements were taken around 11:00 h using five measurements for each replicate with an irradiance setting of 1000 µmol m^{-2} s^{-1}. Irradiance was provided by an LED RGB (red green blue) light source (LI-6400-02B, LI-COR Biosciences).

Determination of photosynthetic photon flux density (PPFD)

Under each shading treatment, photosynthetic flux density (PPFD) was measured with a quantum meter (LI-189, LI-COR Biosciences) during periods of minimal cloud cover. Measurements were recorded hourly from 09:00 to 18:00 h and data from 3 d readings were averaged to provide the mean.

Determination of K uptake and mass balance

Potassium uptake was calculated by multiplying leaflet K concentration at 9, 16, and 23 WAP with the plant DM at 10, 15, and 20 WAP respectively, and expressed in m g plant^{-1} as described by Cedeño et al. (2024). The K mass balance was calculated as the difference between all K inputs and outputs according to Oenema et al. (2003).

Determination of yield

The corms were harvested at 34 WAP when all the senescent plants had dried and entered dormancy. The corms were thoroughly washed to remove all the dirt and then left to dry overnight. The average fresh weight of 20 corms, representing the population in each treatment, was recorded. Yield was expressed in t ha^{-1} by multiplying the average fresh weight by the plant density (166 600 plants ha^{-1}).

Data analysis

Main effects (shade) and nested effects (K rates in each shade) were analyzed using ANOVA at each data interval and means differences were compared using Fisher's least significant difference (LSD) ($\alpha = 0.05$). Regression analysis was carried out to analyze the pattern across growing stages and also the yield. Data obtained was analyzed using JASP (v.0.19.3, University of Amsterdam, The Netherlands) and SAS software (Version 9.4, SAS Institute, Cary, North Carolina, USA).

RESULTS AND DISCUSSION

Main effects of different shading rates on growth, photosynthesis, K uptake efficiency and yield

Generally, the plants vegetative growth were around 25 wk before the crop gradually senescence from 25 to 33 wk after planting (WAP). Corm development was observed at 10 WAP and became dissectible and prominent at 15 WAP. When assessed at 2 WAP, plants under direct sunlight had significantly less vigorous seedlings with visible burning compared to the shaded treatments, and 85% of the plants under direct sunlight died by 12 WAP. Hence, sampling at 5 and 10 WAP in this study included the complete set of shading rates, while sampling at 15 and 20 WAP was carried out only with plants under 50% and 70% shading.

In this study, different shading rates had different range of photosynthetic photon flux density (PPFD) across the day. The highest PPFD range was recorded in 0% shading with range between 397 and 1930 µmol m^{-2} s^{-1} while the lowest range of PPFD was recorded in 70% shading with range of 173-487 µmol m^{-2} s^{-1}. The PPFD range for 50% shading was in between with range of 213-983 µmol m^{-2} s^{-1} (Figure 1).

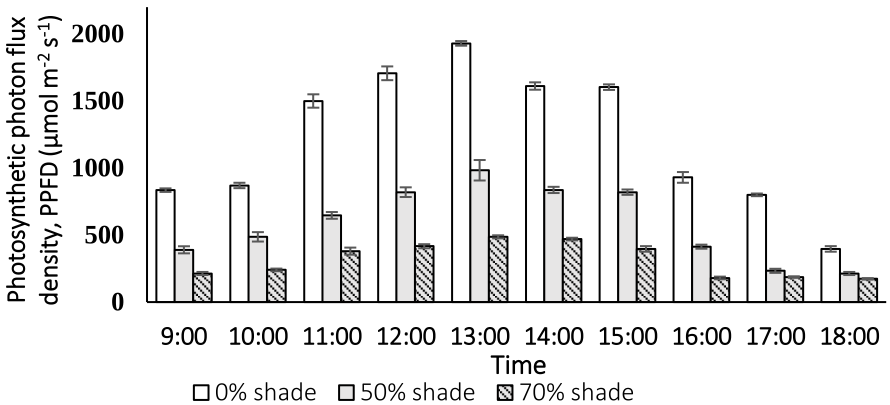

Figure 1. Photosynthetic photon flux density (PPFD) of different shading rates at different times (mean ± SE; n = 3).

Plants under 0% shading died by 12 WAP due to severe light stress that induces photoinhibition. In *Amorphophallus xiei* species, it was reported that light response curves showed a light-saturation point (LSP) between range of 500-700 µmol m^{-2} s^{-1} (Zhang, 2021). Under direct sunlight condition in this study, the PPFD exceeded the optimal range for photosynthesis for duration of 5 h starting from 11:00 until 16:00 h. In shade-tolerant species such as *Psychotria rubra*, the severe prolonged light stress led to early photoinhibition which resulted in photosystem I damage, constrains recovery of photosystem II and depresses whole-plant performance (Huang et al., 2015).

In terms of growth, at 5 and 10 WAP, shade had a significant effect ($P \leq 0.05$) on all measured growth parameters. At both time intervals, regardless of K fertilization level, plants grown under 50% and 70% shade had significantly greater petiole diameter, petiole height, root dry weight, and total dry weight than plants grown under 0% shade, with nonsignificant difference recorded between 50% and 70% shading plants (Table 2).

At 5 WAP, the differences were greater between 0% and 70% shade than between 0% and 50% shade. For instance, the differences in petiole height, leaflet area, and total dry weight under 50% shade relative to 0% shade were 47.03%, 225.76%, and 100%, respectively, whereas the corresponding differences under 70% shade relative to 0% shade were 49.58%, 282.69%, and 133.33%, respectively. At 10 WAP, the previous margin differences were narrowed as plants under 50% shade had relatively the same growth as compared to plants under 70% shade. The differences in petiole height, leaflet area, and total dry weight under 50% shade relative to 0% shade at 10 WAP were 66.51%, 127.61%, and 26.58%, respectively, whereas the corresponding differences under 70% shade relative to 0% shade were 66.02%, 127.62%, and 27.93%, respectively.

At 15 WAP, none of the measured variables differed significantly among shading treatments. As the crop transitioned toward corm filling, shading effects became prominent over time. At 20 WAP, shading significantly ($P \leq 0.05$) affected petiole diameter, leaflet area, fresh corm weight, and dry corm weight, regardless of K fertilization levels (Table 2). Compared with plants under 50% shading, those grown under 70% shade had 10.76% and 25.46% greater petiole diameter and leaflet area respectively, while the corms were 25.51% heavier in fresh weight and 25.56% heavier in dry weight. These gains under 70% shade indicate that irradiance range of 173-487 µmol m^{-2} s^{-1} provided by the 70% shading sustained source activity and canopy efficiency during the C allocation phase to the corm. Shade nets could potentially increase the fraction of diffuse light and modify spectral composition in ways that preserve pigments, delay senescence, and maintain photosynthetic function, supporting sink filling in shade-demanding crops (Pinto et al., 2025). Besides that, ecologically, shade tolerance in *Amorphophallus* species is also linked to its natural habitat in tropical and subtropical forests (Hetterscheid and Ittenbach, 1996), where persistent canopy cover provides natural shading to the plants.

Enhanced growth in terms of petiole diameter, leaflet area and corms mass of plants under 70% shade compared to 50% shade is also attributed to increased K uptake under 70% shade, most notably at 16 WAP when growth is most active. At this stage, plant K uptake under 70% shading was significantly higher (113%) compared to plants under 50% shading, regardless of the K rates applied (Figure 2B).

Table 2. Shading effects of four planting stages and three shading rates on petiole diameter, petiole height, leaflet area, dry weight leaflet, dry weight petiole, dry weight root, total dry weight, dry weight corm and fresh weight corm per plant. **Significant at 1% probability level. *Significant at 5% probability level. ^{ns}Nonsignificant. Means in each column with the different letters within the same planting stage indicate significant differences at $P \leq 0.05$ level according to least significant difference (LSD); n = 12 (5 and 10 WAP), n = 8 (15 and 20 WAP). WAP: Weeks after planting.

Planting stage	Shading rate	Petiole diameter	Petiole height	Leaflet area	Dry weight: Leaflet	Dry weight: Petiole	Dry weight: Root	Dry weight: Corm	Dry weight: Total	Fresh weight corm
	%	mm	cm	cm^2			g			g
5 WAP	0	2.87^b	3.53^b	9.82^c	0.06^b	0.03^b	0.06^b	-	0.15^b	-
	50	3.47^a	5.19^a	31.99^b	0.14^a	0.04^{ab}	0.12^a	-	0.30^a	-
	70	3.55^a	5.28^a	37.58^a	0.16^a	0.06^a	0.13^a	-	0.35^a	-
		**	**	**	**	*	**		**	
10 WAP	0	5.32^b	8.27^b	91.19^b	0.57^b	1.28^a	0.38^b	-	2.22^b	-
	50	6.89^a	13.77^a	207.56^a	1.14^a	1.05^b	0.62^a	-	2.81^a	-
	70	6.55^a	13.73^a	207.57^a	1.05^a	1.02^b	0.77^a	-	2.84^a	-
		**	**	**	**	**	**		*	
15 WAP	50	11.56^a	30.54^a	695.83^a	5.04^a	3.03^a	2.39^a	2.86^a	13.31^a	9.04^a
	70	11.69^a	31.3^a	719.03^a	4.55^a	3.11^a	2.53^a	2.84^a	13.04^a	9.54^a
		ns	ns	ns	ns	ns	ns	ns	ns	ns
20 WAP	50	15.33^b	41.13^a	1177.23^b	7.67^a	8.88^a	1.68^a	4.39^b	22.63^a	22.93^b
	70	16.98^a	43.180^a	1476.93^a	8.77^a	9.96^a	1.80^a	5.51^a	28.17^a	28.79^a
		**	ns	**	ns	ns	ns	*	ns	*

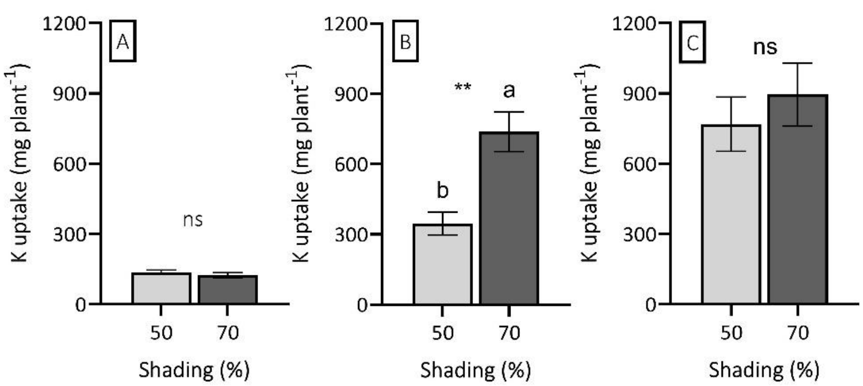

Figure 2. Effects of different shading rates on K uptake at 9 (A), 16 (B), and 23 (C) weeks after planting (WAP) (mean ± SE; n = 8) per plant. **Significant at 1% probability level. ns: Nonsignificant. Means in each graph with the different letter indicate significant differences at $P \leq 0.05$% level according to least significant difference (LSD).

When regressed against WAP, plant K uptake in both shading rates followed a polynomial growth pattern. From the polynomial equation, the rate of K uptake in 70% shading plants was also found to be more rapid (27.63% faster) compared to 50% shading plants across the growing stages. The higher coefficient for the linear term in 70% shading (22.76) compared to 50% shading (0.06) indicated that plant K uptake under 70% shading was more rapid in the early and middle stages of growth compared to plants under 50% shading. In contrast, plant K uptake under 50% shading was observed to increase in the later stages of growth, expressed by the higher value of coefficient for polynomial term (1.43) compared to 70% shading (0.88) (Figure 3).

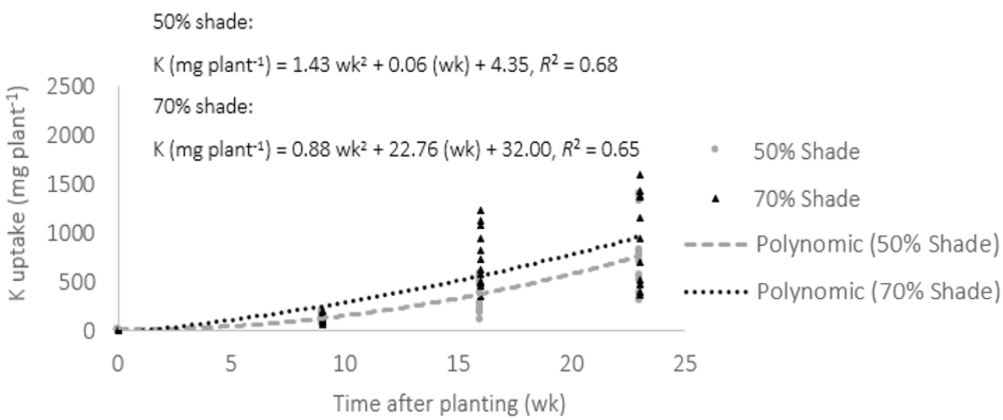

Figure 3. Polynomial regression of K uptake for different shading rates at different time after planting.

The results indicate that under the more favorable microclimate of 70% shade, K uptake was both greater and more efficient, as evidenced by significantly ($P \leq 0.01$) less (29.06% smaller) K mass balance relative to 50% shade (Table 3). This efficiency aligns with enhanced source capacity and sink development under 70% shade in which at 20 WAP, higher corm mass signaled for stronger sink strength and sustained assimilate demand. As source activity rises, phloem demand intensifies and plants typically up-regulate K acquisition to stabilize carbon gain and support growth (Wang and Wu, 2017).

Table 3. Effects of different shading rates on K mass balance. **Significant at 1% probability level. *Significant at 5% probability level. ^{ns}Nonsignificant. Means in each column with the different letters within the same shading rate indicate significant differences at $P \leq 0.05$ level according to least significant difference (LSD), $n = 8$.

Shading rate	K mass balance
%	t ha^{-1}
50	-25.60^{a}
70	-33.04^{b}
	**

Notably, because K uptake was more pronounced under 70% shading, the soil K content was depleted to a greater extent than under 50% shading, supporting the negative association between plant K uptake and soil K reserves. At the middle stage, the soil K content under 70% shading was approximately 6.02% lower than that recorded under 50% shading, while at the post-harvest stage it was about 7.21% lower. Even though there were nonsignificant difference among them at the middle (Figure 4B) and post-harvest stage (Figure 4C), the polynomial regression revealed that the maximum (vertex) value of soil K reserve in 50% shading was 0.69 $cmol_c$ kg^{-1} soil while for 70% shading was 4.35% lower at 0.66 $cmol_c$ kg^{-1} soil (Figure 5).

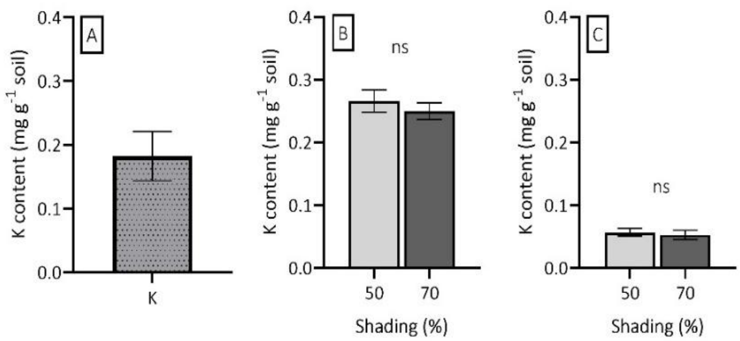

Figure 4. Effects of different shading rates at pre-plant (A), middle 16 WAP (B) and post-harvest 34 WAP (C) on soil K content (mean ± SE; n = 8). [ns]Nonsignificant. Means in each graph with the different letter indicate significant differences at $P \leq 0.05\%$ level according to least significant difference (LSD).

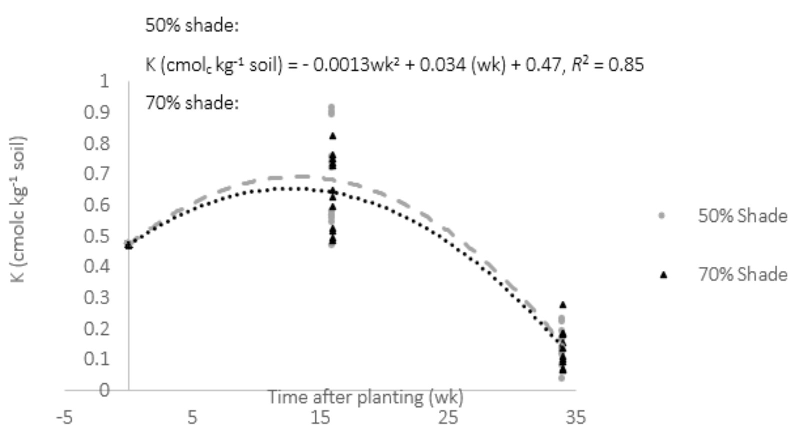

Figure 5. Polynomial regression of K in soil for different shading rates at different time after planting.

Photosynthesis is a key metabolic process in plants, and its efficiency greatly influences plant growth, yield and resistance (Qin et al., 2019). Increases in photosynthetic rate are associated with higher yields, reflecting greater assimilate formation and more effective allocation to the storage organ. In *A. konjac* for instance, Qin et al. (2019) reported that plants under 50% shading had significantly higher photosynthesis rate (10.37 µmol CO_2 m^{-2} s^{-1}) compared to plants under direct sunlight (8.27 µmol CO_2 m^{-2} s^{-1}) and corm weight of those plants under 50% shading was significantly higher (33.28%) compared to under sunlight. This trend is in line with results obtained in this study in which 70% shading plants had significantly ($P \leq 0.01$) higher (15.71%) photosynthesis rate compared to 50% shading plants (Figure 6A). In 0% shading plants however, photoinhibition from the light stress significantly reduced the plants' photosynthetic efficiency by 3.2- and 3.9-fold, as compared to 50% and 70% shading, respectively (Figure 6A).

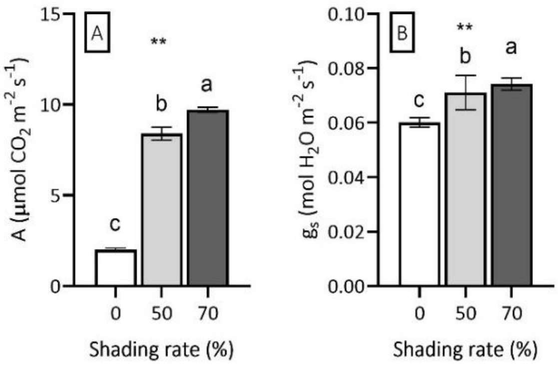

Figure 6. Effects of different shading rates on photosynthesis rate (A) (A) and stomatal conductance (g_s) (B). (mean ± SE; *n* = 8). **Significant at 1% probability level. Means in each graph with the different letter indicate significant differences at *P* ≤ 0.05 level according to least significant difference (LSD).

Attributed to greater assimilate production and partitioning to the storage organ provided by the higher photosynthesis rate, yield (fresh weight corm per plant) of plants under 70% shading was 27.9% higher compared to plants under 50% shading (Figure 7A). Photosynthesis is closely linked to stomatal function because higher stomatal conductance (g_s) increases CO_2 diffusion into the leaf, supporting higher assimilation (Lawson and Vialet-Chabrand, 2019). This is in line with results obtained in this study where g_s of treatments with higher net photosynthesis rate; 70% shading plants were significantly ($P \leq 0.01$) higher by 4.37% compared to 50% shading plants (Figure 6B).

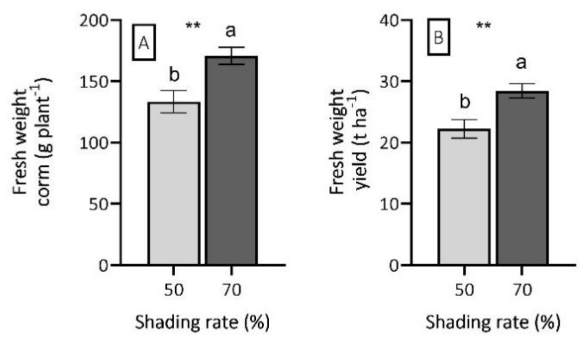

Figure 7. Effects of different shading rates on fresh weight corm per plant (A) and fresh weight yield per hectare (B) (mean ± SE; *n* = 8). **Significant at 1% probability level. Means in each graph with the different letter indicate significant differences at *P* ≤ 0.05 level according to least significant difference (LSD).

Stomatal conductance is strongly regulated by K since K^+ uptake by guard cells drives turgor and stomatal opening (Wang and Wu, 2017). In this study, even though the K uptake between 50% and 70% shading plants were not significantly different at 9 WAP (Figure 2A), g_s between these two treatments which was taken 1 wk after; 10 WAP were significantly different (Figure 6B). Since sampling was not done at 10 WAP, presumably, K uptake in 70% shading plants increased tremendously beyond 9 WAP as evident by huge margin (113%) of these two shading at 16 WAP (Figure 2B). Furthermore, K also powers phloem loading and long-distance assimilate transport, strengthening sink development and biomass partitioning to storage organs (Zörb et al., 2014).

When converted to tonne per hectare, the yield for plants under 50% shading and 70% shading, regardless of K rates given was 22.24 and 28.44 t ha^{-1}, respectively (Figure 7B). Besides linked to net photosynthesis rate, this enhancement in 70% shading coincided with earlier and greater K uptake during the active growth phase, indicating that microclimate optimisation under higher shade level improved K acquisition and its conversion into storage biomass.

Effects of different K rates nested in different shading on growth, photosynthesis, K uptake efficiency and yield
At 5 WAP (Table 4), K fertilization had no detectable effect on most parameters taken. The exceptions were petiole diameter under 50% shade and leaflet area under 70% shade. Compared with the unfertilized control (T1), K-fertilized plants (75, 150, 225 kg ha^{-1}, T2, T3, T4, respectively) had bigger petiole diameter under 50% shade, increasing by 22.15%, 22.82%, and 21.48% for T2, T3, and T4, respectively, and larger leaflet area under 70% shade, increasing by 26.75%, 18.27%, and 18.73% for T2, T3, and T4, respectively. The absence of K rate effects on the remaining parameters can be attributed to seedling physiology at 5 WAP. At this early stage, plants were small and had only recently produced the first true leaf. Before true leaf expansion, growth is largely supported by reserves from the cotyledon, which limits the expression of treatment differences (Gommers and Monte, 2018). Even so, rapidly developing and fertilizer-sensitive phenological traits such as petiole diameter and leaflet area exhibited an early response to K supply.

Table 4. Effects of different K rates nested in three different shading rates at 5 wk after planting on petiole diameter, petiole height, leaflet area, dry weight leaflet, dry weight petiole, dry weight root and total dry weight per plant. **Significant at 1% probability level. *Significant at 5% probability level. ^{ns}Nonsignificant. Means in each column with the different letters within the same shading rate indicate significant differences at $P \leq 0.05$ level according to least significant difference (LSD), $n = 48$.

Shading rate	K rate	Petiole diameter	Petiole height	Leaflet area	Dry weight Leaflet	Dry weight Petiole	Dry weight Root	Dry weight Total
%	kg ha^{-1}	mm	cm	cm^2	g			
0	T1 (0)	2.53^a	3.39^a	9.75^a	0.07^a	0.03^a	0.06^a	0.17^a
	T2 (75)	2.83^a	3.60^a	9.95^a	0.06^a	0.03^a	0.06^a	0.15^a
	T3 (150)	3.02^a	3.49^a	9.35^a	0.04^a	0.03^a	0.06^a	0.12^a
	T4 (225)	3.10^a	3.64^a	10.22^a	0.08^a	0.03^a	0.05^a	0.16^a
		ns	ns	ns	ns	ns	ns	ns
50	T1 (0)	2.98^b	4.56^a	31.87^a	0.12^a	0.04^a	0.14^a	0.29^a
	T2 (75)	3.64^a	5.11^a	28.47^a	0.16^a	0.04^a	0.10^a	0.30^a
	T3 (150)	3.66^a	5.63^a	36.60^a	0.16^a	0.04^a	0.14^a	0.34^a
	T4 (225)	3.62^a	5.48^a	31.02^a	0.15^a	0.03^a	0.08^a	0.27^a
		*	ns	ns	ns	ns	ns	ns
70	T1 (0)	3.25^a	5.05^a	32.41^b	0.15^a	0.03^a	0.11^a	0.30^a
	T2 (75)	3.59^a	5.14^a	41.08^a	0.17^a	0.05^a	0.16^a	0.38^a
	T3 (150)	3.73^a	5.90^a	38.33^a	0.16^a	0.09^a	0.15^a	0.37^a
	T4 (225)	3.63^a	5.05^a	38.48^a	0.15^a	0.07^a	0.12^a	0.33^a
		ns	ns	*	ns	ns	ns	ns

At 10 WAP (Table 5), the effect of K rates was more pronounced under 70% shade than under 50% shade. Under 50% shade, only petiole diameter responded significantly to K rates, whereas under 70% shade, all measured traits, except petiole height and root dry weight, showed significant responses. This pattern indicates that 70% shade places *A. muelleri* in a microclimatic window where K availability more strongly promotes growth. The alignment between a shade-adapted canopy and reduced light stress likely facilitates earlier and greater K acquisition, amplifying phenology responses. Consistent with this interpretation, K uptake at 9 WAP (1 wk before 10 WAP) under 70% shade was significantly ($P \leq 0.05$) higher in K-fertilized plants (T2, T3, T4) than in the unfertilized control (T1); increasing by 49.97%, 87.81%, and 53.59% for T2, T3, and T4, respectively.

Nonsignificant differences among K treatments were detected under 50% shade (Figure 8A). The greater K uptake under 70% shade therefore supported enhanced vegetative growth, which was subsequently expressed across most measured parameters.

Table 5. Effects of different K rates nested in three different shading rates at 10 wk after planting on petiole diameter, petiole height, leaflet area, dry weight leaflet, dry weight petiole, dry weight root and total dry weight per plant. **Significant at 1% probability level. *Significant at 5% probability level. nsNonsignificant. Means in each column with the different letters within the same shading rate indicate significant differences at $P \leq 0.05$ level according to least significant difference (LSD), n = 48.

Shading rate	K rate	Petiole diameter	Petiole height	Leaflet area	Dry weight Leaflet	Dry weight Petiole	Dry weight Root	Dry weight Total
%	kg ha^{-1}	mm	cm	cm^2	g			
0	T1 (0)	4.58^a	6.28^a	69.70^a	0.41^a	1.21^a	0.44^a	2.05^a
	T2 (75)	5.39^a	8.25^a	85.69^a	0.51^a	1.29^a	0.27^a	2.06^a
	T3 (150)	5.35^a	9.20^a	101.16^a	0.63^a	1.38^a	0.40^a	2.41^a
	T4 (225)	5.95^a	9.37^a	108.22^a	0.71^a	1.26^a	0.40^a	2.38^a
		ns	ns	ns	ns	ns	ns	ns
50	T1 (0)	5.62^b	11.03^a	150.38^a	0.90^a	0.97^a	0.52^a	2.38^a
	T2 (75)	7.05^a	14.01^a	222.56^a	1.25^a	1.06^a	0.66^a	2.97^a
	T3 (150)	7.46^a	15.78^a	230.55^a	1.23^a	1.17^a	0.64^a	3.03^a
	T4 (225)	7.41^a	14.26^a	226.78^a	1.20^a	1.00^a	0.67^a	2.87^a
		*	ns	ns	ns	ns	ns	ns
70	T1 (0)	5.67^c	11.89^a	148.07^b	0.81^c	0.88^b	0.65^a	2.34^c
	T2 (75)	6.55^b	13.30^a	226.58^a	1.17^{ab}	1.07^a	0.80^a	3.04^{ab}
	T3 (150)	7.03^a	15.09^a	250.23^a	1.24^a	1.15^a	0.92^a	3.30^a
	T4 (225)	6.95^{ab}	14.66^a	205.41^a	0.99^{bc}	0.99^{ab}	0.72^a	2.70^{bc}
		*	ns	*	*	*	ns	**

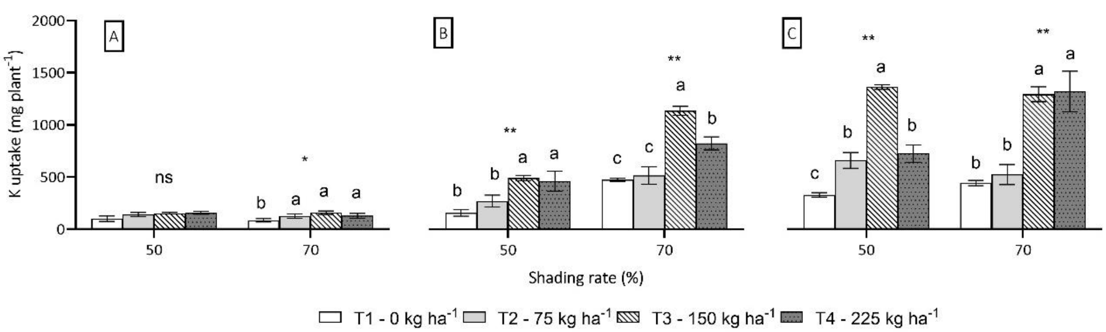

Figure 8. Effects of different K rates nested in different shading rates at 9 (A), 16 (B) and 23 wk after planting (WAP) (C) on K uptake per plant (mean ± SE; n = 32). **Significant at 1% probability level. *Significant at 5% probability level. nsNonsignificant. Means in each graph with the different letters within the same shading rate of the same planting time indicate significant differences at $P \leq 0.05$ level according to least significant difference (LSD).

Plants receiving T3 under 70% shading achieved the greatest total dry weight, which was 22.2% higher than that of plants supplied with the higher rate (T4) (Table 5). These demonstrated that at 10 WAP, increasing K beyond the T3 level did not enhance C assimilation in *A. muelleri* and instead was associated with a reduction. A similar pattern was observed for petiole height, leaflet area, and petiole diameter, although these differences were nonsignificant. These patterns indicate that excess external K triggers luxury uptake without yield benefit and lowers K-use efficiency, a pattern reported across cereals and other crops (Dhillon et al., 2019).

At 15 WAP (Table 6), K rate significantly ($P \leq 0.05$) affected most growth parameters under both 50% and 70% shade. The onset of K rates effect under less favorable conditions (50% shade) was delayed until 15 WAP, whereas under 70% shade they were already evident at 10 WAP. Plant growth is tightly coupled to nutrient uptake dynamics at the soil and root interface, where root demand, transport capacity, and soil supply jointly regulate biomass accumulation and yield (Hinsinger, 2001). In particular, K supports turgor-driven expansion, stomatal regulation, and enzyme activation, so growth responses often track the plant's ability to acquire K from the soil pools available in situ (Rietra et al., 2017). Accordingly, the association between growth at 15 WAP with the K uptake and K soil reserve measured at the nearest sampling point - 16 WAP was evaluated. It is demonstrated that at 15 WAP under 50% shading, there was nonsignificant difference in all growth parameters taken between T3 and T4 plants (Table 6). Coherently, the K uptake in these treatments also showed nonsignificant difference (Figure 8B). This implies that the unlike T3, the additional K applied in T4 (225 kg ha^{-1}) was not absorbed by the plants and therefore remained in the soil of T4 plants. This is evidenced in the results where the soil K content for T4 plants was significantly higher at middle (Figure 9B) and post-harvest stage (Figure 9C) with margin difference of 34.62% and 42.86%, respectively, as compared to plants.

Table 6. Effects of different K rates nested in two different shading rates at 15 wk after planting on petiole diameter, petiole height, leaflet area, dry weight leaflet, dry weight petiole, dry weight root, total dry weight, dry weight corm and fresh weight corm per plant. **Significant at 1% probability level. *Significant at 5% probability level. ^{ns}Nonsignificant. Means in each column with the different letters within the same shading rate indicate significant differences at $P \leq 0.05$ level according to least significant difference (LSD), $n = 32$.

Shading rate	K rate	Petiole diameter	Petiole height	Leaflet area	Dry weight Leaflet	Dry weight Petiole	Dry weight Root	Dry weight Corm	Dry weight Total	Fresh weight corm
%	kg ha^{-1}	mm	cm	cm^2	g	g	g	g	g	g
50	T1 (0)	8.95^{c}	20.60^{c}	353.15^{c}	2.44^{c}	1.54^{c}	1.94^{b}	2.40^{a}	8.31^{c}	6.31^{b}
	T2 (75)	10.23^{b}	30.70^{b}	509.33^{b}	3.88^{b}	2.63^{b}	2.14^{b}	2.93^{a}	11.58^{b}	8.04^{b}
	T3 (150)	13.72^{a}	36.35^{a}	964.88^{a}	6.68^{a}	4.03^{a}	2.79^{a}	2.98^{a}	16.47^{a}	10.62^{a}
	T4 (225)	13.34^{a}	34.50^{a}	955.96^{a}	7.17^{a}	3.93^{a}	2.68^{a}	3.12^{a}	16.89^{a}	11.19^{a}
		**	**	**	**	**	**	ns	**	**
70	T1 (0)	9.66^{c}	22.50^{b}	426.46^{c}	2.47^{b}	1.69^{d}	2.14^{b}	2.53^{a}	8.82^{c}	7.32^{a}
	T2 (75)	11.27^{bc}	31.75^{a}	652.11^{bc}	4.02^{b}	2.48^{c}	2.05^{b}	2.56^{a}	11.11^{bc}	7.87^{a}
	T3 (150)	13.62^{a}	36.00^{a}	1083.89^{a}	7.34^{a}	5.07^{a}	2.96^{a}	3.65^{a}	19.02^{a}	14.01^{a}
	T4 (225)	12.22^{ab}	34.95^{a}	713.68^{b}	4.39^{a}	3.21^{b}	2.98^{a}	2.62^{a}	13.20^{b}	8.96^{a}
		*	**	**	**	**	*	ns	**	ns

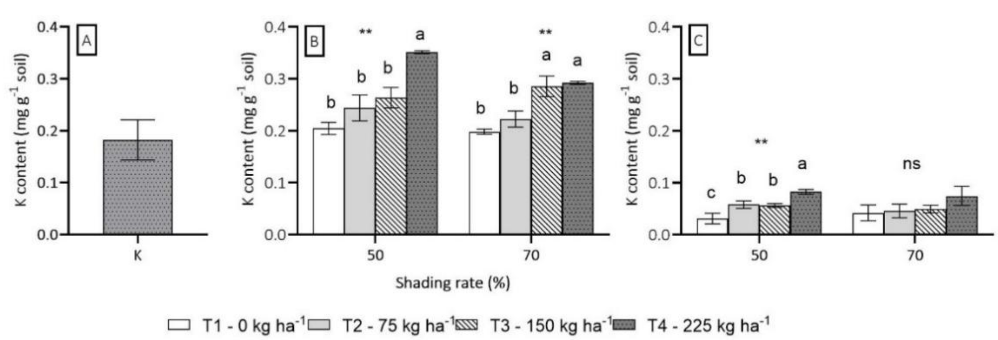

Figure 9. Effects of different K rates nested in different shading rates at pre-plant (A), middle 16 WAP (B) and post-harvest 34 WAP (C) on soil K content (mean ± SE; $n = 32$). **Significant at 1% probability level. ^{ns}Nonsignificant. Means in each graph with the different letters within the same shading rate of the same planting time indicate significant differences at $P \leq 0.05$ level according to least significant difference (LSD). WAP: Weeks after planting.

At 70% shade, increased K rates from T3 to T4 failed to increase K uptake and, in fact, led to a significant reduction by 27.40% comparing to T3 (Figure 8B). Consequently, leaflet area, petiole dry weight and total dry weight of T4 plants were 34.16%, 36.69% and 30.60% lower, respectively compared to T3 plants (Table 6). It was also observed that at 16 WAP, the soil K reserve in T4 for plants under 70% shade did not remain high even though the rate given was the highest and the uptake was significantly lower than T3. Ironically, the results showed that the soil K content in T4 plants was the same with T3 plants at 16 WAP (Figure 9B), implying excessive K rate led to K losses. Potassium is very soluble and can be leached to depth or to surface waters. Since K is bound to clays and organic materials, and adsorbed K is mostly associated with fine soil particles, it can be eroded with particulate material in runoff water and by strong winds. In this study, general losses can be expected in the presence of drainage when K inputs exceed the sum of K holding capacity and plant uptake as described by Goulding et al. (2021).

The same growth trend continued at 20 WAP where all of the growth parameters measured for T3 plants under 70% shading were relatively higher compared to T4 plants, even though they were not significantly different (Table 7). This implies that T4 plants experienced slower growth during the first 15 wk, after which they gradually narrowed the gap with T3.

Table 7. Effects of different K rates nested in two different shading rates at 20 wk after planting on petiole diameter, petiole height, leaflet area, dry weight leaflet, dry weight petiole, dry weight root, total dry weight, dry weight corm and fresh weight corm per plant. **Significant at 1% probability level. *Significant at 5% probability level. ^{ns}Nonsignificant. Means in each column with the different letters within the same shading rate indicate significant differences at $P \leq 0.05$ level according to least significant difference (LSD), n = 32.

Shading rate	K rate	Petiole diameter	Petiole height	Leaflet area	Dry weight					Fresh weight corm
					Leaflet	Petiole	Root	Corm	Total	
%	kg ha^{-1}	mm	cm	cm^2	g					g
50	T1 (0)	11.57^{d}	28.00^{c}	866.14^{c}	5.05^{c}	2.53^{d}	1.20^{c}	2.31^{c}	11.09^{d}	10.85^{c}
	T2 (75)	13.24^{c}	35.35^{b}	952.87^{c}	7.20^{b}	4.53^{c}	1.75^{a}	4.51^{b}	17.98^{c}	21.66^{b}
	T3 (150)	19.58^{a}	51.50^{a}	1624.81^{a}	10.74^{a}	19.89^{a}	2.33^{a}	6.37^{a}	39.33^{a}	35.00^{a}
	T4 (225)	16.95^{b}	49.65^{a}	1265.10^{b}	7.77^{b}	8.57^{b}	1.44^{bc}	4.37^{b}	22.14^{b}	24.21^{b}
		**	**	**	**	**	**	**	**	**
70	T1 (0)	14.81^{b}	36.15^{b}	1068.01^{a}	6.55^{a}	3.67^{b}	1.12^{b}	4.45^{b}	15.78^{b}	23.58^{b}
	T2 (75)	16.60^{ab}	37.00^{b}	1240.39^{a}	7.11^{a}	4.79^{b}	1.62^{ab}	4.00^{b}	17.51^{b}	21.41^{b}
	T3 (150)	18.65^{a}	51.00^{a}	1810.87^{a}	11.17^{a}	15.38^{a}	2.48^{a}	7.82^{a}	36.84^{a}	40.18^{a}
	T4 (225)	17.88^{a}	48.25^{a}	1788.46^{a}	10.25^{a}	16.03^{a}	1.98^{ab}	5.57^{b}	33.81^{a}	30.00^{ab}
		*	*	ns	ns	*	*	*	*	*

Due to the better growth performance in the first 15 wk in T3 plants under 70% shading that led to greater C assimilation and sink to the corm, the dry weight of corm in T3 plants at 20 WAP (Table 7) were found to be significantly heavier ($P \leq 0.05$) compared to other treatments. The difference in comparison to T1, T2 and T4 was 75.73%, 95.50% and 40.39% higher, respectively.

This trend however did not sustain until the harvest stage. At harvest (34 WAP), T4 plants under 70% shading had the heaviest weight of fresh corm; 11.63%, 26.44% and 42.50% higher than T3, T2 and T1 plants, respectively (Figure 10A). The difference, however, was only significant to T1 and T2, but not with T3 (Figure 10A). The K mass balance between T3 and T4 plants under 70% shading also showed nonsignificant difference among them (Table 8). This demonstrated that under 70% shading, increment of T3 to T4 not only add additional fertilizer cost but was also inefficient in increasing K uptake efficiency and corm yield enhancement. This pattern is consistent with the luxury consumption region of the nutrient response curve, where extra K is taken up but does not translate into additional growth or yield (Penn et al., 2023).

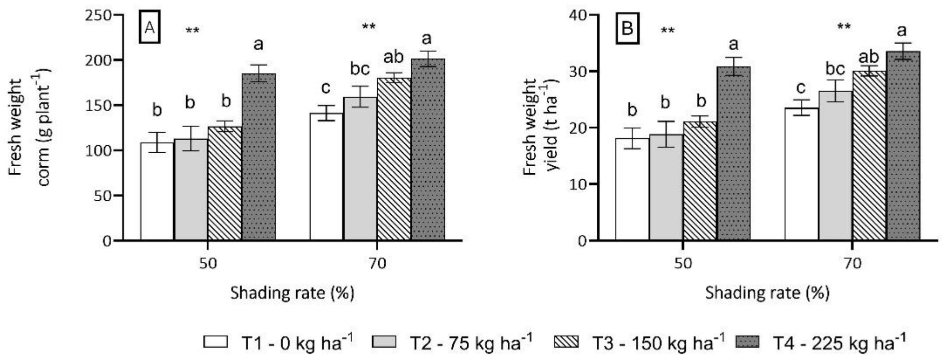

Figure 10. Effects of different K rates nested in different shading rates on fresh weight corm per plant (A) and fresh weight yield (B) (mean ± SE; *n* = 32). **Significant at 1% probability level. Means in each graph with the different letters within the same shading rate indicate significant differences at $P \leq 0.05$ level according to least significant difference (LSD).

Table 8. Effects of different K rates nested in two different shading rates on K mass balance. **Significant at 1% probability level. *Significant at 5% probability level. nsNonsignificant. Means in each column with the different letters within the same shading rate indicate significant differences at $P \leq 0.05$ level according to least significant difference (LSD), *n* = 32.

Shading rate	K rate	K mass balance
%	kg ha^{-1}	t ha^{-1}
50	T1 (0)	-20.14^{a}
	T2 (75)	-21.08^{a}
	T3 (150)	-27.38^{ab}
	T4 (225)	-33.79^{b}
		*
70	T1 (0)	-25.46^{a}
	T2 (75)	-31.15^{b}
	T3 (150)	-36.49^{c}
	T4 (225)	-39.03^{c}
		**

Relationship between photosynthesis rate and yield gain is typically positively correlated (Keller et al., 2024). In this study, measurements of photosynthesis rate that was done at 10 WAP did not coherently translated to the yield pattern. Compared to other treatments, under 50% shade, photosynthetic rate was significantly ($P \leq 0.01$) highest in T2 compared to T1, T3, T4 by 43.44%, 6.68% and 41.89% respectively (Figure 11). Under 70% shading, T3 plants had significantly ($P \leq 0.01$) higher photosynthesis rate compared to T1, T2 and T4 by 13.63%, 3.30% and 9.77%, respectively (Figure 11). The yield trend however was different where T4 had significantly higher yield compared to other treatments in 50% shading while in 70% shading, the difference was only significant to T1 and T2 (Figure 10). A plausible explanation for this is that growth of T4 plants were slow during the first 15 wk and accelerated later during the last 10 wk before senescence at 25 WAP. Consequently, photosynthesis measured at 10 WAP does not reflect the eventual yield pattern. Had measurements been taken later (at 16 WAP), when K uptake became impactful (Figure 8B), the photosynthetic trend across treatments would likely have aligned more closely with the yield response. Nonetheless, due to resource constrains, only a single measurement time point was included in this study.

Yield regression analysis revealed that linear regression best fitted the data for 70% shading, with the linear model explained 74% of the yield variation (Figure 12). With every unit of K rate increased, the yield will increase by 0.046 t ha^{-1} (46 kg ha^{-1}) and the model's predicted yield at 0 kg ha^{-1} is equivalent to its intercept, 23.64 t ha^{-1}. It is important to note that this linear slope should be interpreted as an average marginal response within the observed K range, not a constant gain at all rates. In fertilizer response work, yield increments typically diminish as the rate increases, because other factors become limiting and the crop approaches its physiological or management ceiling as described by the Liebig's law of minimum theory (Ferreira et al., 2017). Consequently, response curves often bend and level off rather than remaining linear (Culman et al., 2023). The nonsignificant increment of yield from T3 to T4 in the findings (Figure 10) suggest that in *A. muelleri*, the onset of levelling off in yield curve is somewhere between 150-225 kg ha^{-1}.

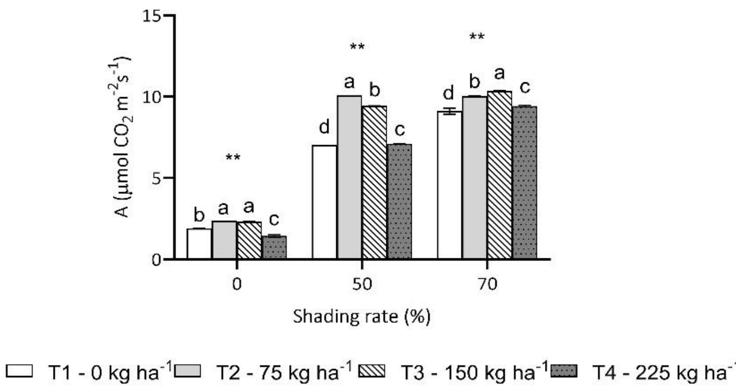

Figure 11. Effects of different K rates nested in different shading rates on photosynthesis rate (A) (mean ± SE; *n* = 48). **Significant at 1% probability level. Means in each column with the different letters within the same shading rate indicate significant differences at $P \leq 0.05$ level according to least significant difference (LSD).

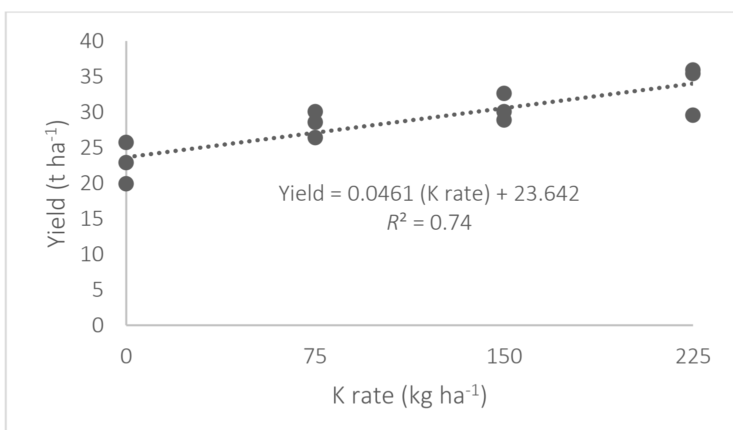

Figure 12. Linear regression of yield for different K rates in 70% shading.

The yield response curve to K under 50% shade differed from that under 70% shade. In the less favorable environment of 50% shading - PPFD of 213-983 µmol m^{-2} s^{-1}, increasing K rate from T1 to T3 did not result in a significant yield gain, whereas raising it to T4 produced a significant increase in yield. Plants treated with T4 had 46.36%, 63.92% and 70.20% higher yield as compared to T3, T2 and T1 (Figure 8). The K mass balance for T4 plants was also significantly smaller compared to T1 and T2, implying a good response in K uptake efficiency compared to T1 and T2 (Table 8). Due to the steep increment from T3 to T4, yield respond curve for 50% shading was best fitted using polynomial equation as described in Figure 13.

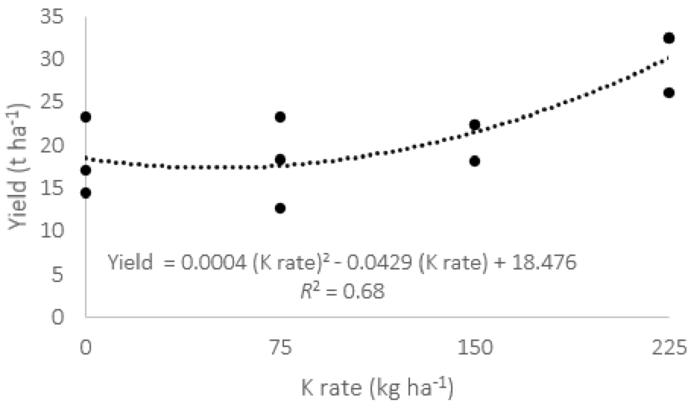

Figure 13. Polynomial regression of yield for different K rates in 50% shading.

A field trial in Indonesia by Sudoyo et al. (2024) investigated the effects of varying soil organic C (SOC) on yield of *A. muelleri* planted using seeds. Application of 117 t ha^{-1} goat manure as reported in the trial managed to increase SOC from 1.79% to 4.0% combining the manure with 150 kg ha^{-1} NPK compound fertilizer (NPK green), the corm yield was reported at 185.24 g plant^{-1} fresh weight. However, the authors did not indicate whether plants were grown under shade netting or in full sun. In this present study, a substantially lower organic input of 5 t ha^{-1} chicken manure, together with straight fertilizers - 50 kg ha^{-1} N, 200 kg ha^{-1} P and 150 kg ha^{-1} K (T3) achieved a comparable yield of 180.51 g plant^{-1} fresh weight (Figure 10A). Given that straight fertilizers were typically cheaper than compound formulations and that the manure rate was 23.4-fold lower, these results indicate that similar yields can be obtained at markedly reduced input costs.

Another study in China by Zhang et al. (2010) reported that yield of *A. muelleri* planted from seeds was at 1200 g plant^{-1}; 6.6 times higher than optimum yield result from this study (Figure 10A). The author, however, did not state the fertilizer regime used in the study and the higher yield was explainable since the trial was conducted in a controlled environment system inside a mini greenhouse. These factors suggest that under preferable growth condition, the crop's potential yield can be achieved.

According to Santosa et al. (2003), the potential yield of *A. muelleri* can reach 40 t ha^{-1} fresh weight. Still, the average productivity at farmer level is only 6-10 t ha^{-1}. In China, the potential yield is reported to be 75 t ha^{-1} but the actual yield in the traditional cultivation of *A. muelleri* in Yunnan is much lower at about 13.5-18.9 t ha^{-1} only (Zhang et al., 2010). The low on-farm productivity of *A. muelleri* is likely due to non-intensive cultivation practices, particularly insufficient fertilizer and irrigation (Santosa et al., 2011), and the use of low-quality planting materials (Zhang et al., 2010). In addition, nutrient management plays a critical role in increasing the yield potential. Applying fertilizer at times that match the plant's nutrient demand can improve uptake, enhance growth, and ultimately increase yield.

Optimum application time of K fertilization in konjac

The temporal dynamics of soil K content exhibited a distinct pattern across the planting cycle, whereby concentrations increased from the pre-planting stage to the mid-growth phase and subsequently declined towards the post-harvest stage (Figures 14 and 15). This trend was consistent irrespective of shading intensities and K fertilization rates applied. Polynomial regression analysis revealed that soil K content over time conformed to a quadratic function, with the vertex (maximum point) representing the inflection point at which soil K reserves began to diminish. This turning point reflects the onset of accelerated nutrient depletion, primarily attributable to plant uptake during active growth (Bender et al., 2013). This turnover point varied across K fertilization rates and shading levels.

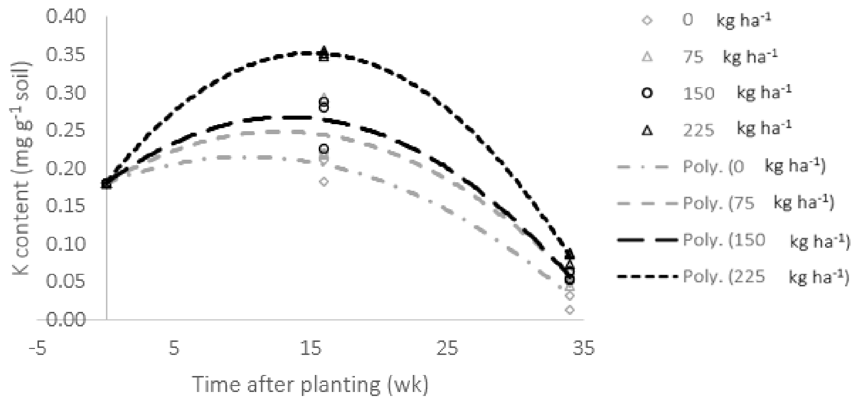

Figure 14. Polynomial regression of soil K content across pre-plant, mid and post-harvest stages for different K rates in 50% shading.

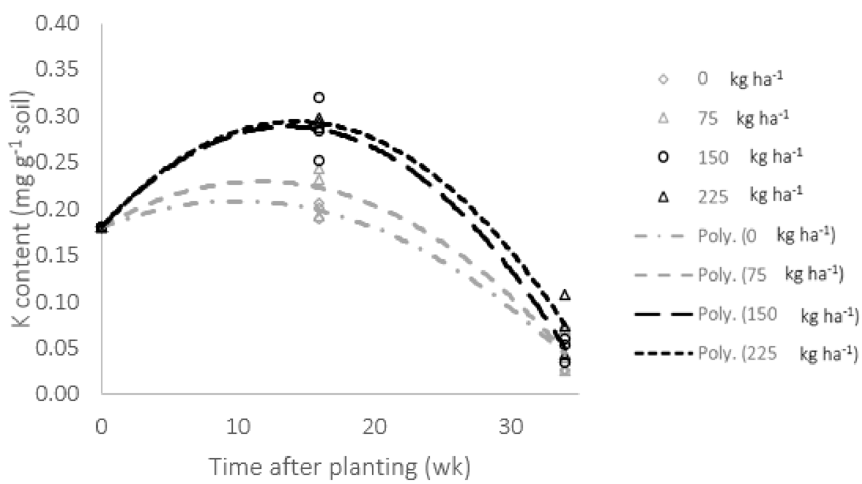

Figure 15. Polynomial regression of soil K content across pre-plant, mid and post-harvest stages for different K rates in 70% shading.

Under 50% shading, the turnover point was earliest in the unfertilized treatment, T1 (0 kg ha^{-1}) - 11.3 WAP. With K application, the turnover point was delayed, ranging from 13.1 WAP in T3 (150 kg ha^{-1}) to as late as 14.3 WAP in T4 (225 kg ha^{-1}) (Table 9). This finding implies that higher K input effectively prolonged the soil K reserves before depletion began. At 70% shading, however, the unfertilized treatment (T1) exhibited an even earlier turnover point at 9.5 WAP, suggesting more rapid depletion of soil K in shaded conditions when no K was supplied. Fertilized treatments moderated this effect, with T2 (75 kg ha^{-1}) extending the turnover point to 10.8 WAP, while both T3 (150 kg ha^{-1}) and T4 (225 kg ha^{-1}) delayed it further to 13.3 WAP (Table 10).

From a nutrient management perspective, the turnover point provides a critical reference for optimizing fertilizer scheduling. Under 50% and 70% shading, the unfertilized treatment (T1) exhibited the earliest turnover point at 11.3 and 9.5 WAP respectively, suggesting that soil K reserves were rapidly depleted during the early vegetative phase due to high canopy expansion and increased nutrient demand. This finding suggests that in order to synchronize with the critical period of maximum K uptake, K fertilizer should be applied before 11 WAP in 50% shading conditions whereas in 70% shading condition, before 9 WAP, with few considerations such as pre-plant K status and soil characteristics need to be taken into considerations. Application that is not aligned with this demand risks nutrient inefficiency such as leaching losses. Potassium is a highly mobile cation in the soil solution, and while it can be retained on exchange sites of clay minerals and organic matter, it is also prone to leaching, particularly in coarse-textured soils with low cation exchange capacity (CEC) or under conditions of high rainfall and irrigation. Potassium leaching is usually less severe in fine-textured soils but becomes a significant concern in sandy or well-drained soils (Zörb et al., 2014).

Table 9. Polynomial equation and the turnover point for different K rates in 50% shading.

K rate (kg ha^{-1})	Polynomial equation (50% shading)	Turnover point (WAP)
T1 (0)	$y = -0.0003x^2 + 0.0068x + 0.18$, $R^2 = 0.97$	11.3
T2 (75)	$y = -0.0004x^2 + 0.0107x + 0.18$, $R^2 = 0.93$	13.4
T3 (150)	$y = -0.0005x^2 + 0.0131x + 0.18$, $R^2 = 0.96$	13.1
T4 (225)	$y = -0.0008x^2 + 0.0228x + 0.18$, $R^2 = 0.99$	14.3

Table 10. Polynomial equation and the turnover point for different K rates in 70% shading.

K rate (kg ha^{-1})	Polynomial equation (70% shading)	Turnover point (WAP)
T1 (0)	$y = -0.0003x^2 + 0.0057x + 0.18$, $R^2 = 0.97$	9.5
T2 (75)	$y = -0.0004x^2 + 0.0086x + 0.18$, $R^2 = 0.95$	10.8
T3 (150)	$y = -0.0006x^2 + 0.0159x + 0.18$, $R^2 = 0.97$	13.3
T4 (225)	$y = -0.0006x^2 + 0.0160x + 0.18$, $R^2 = 0.97$	13.3

Nonetheless, this suggestion is contradictory than what reported in the previous study by Santosa et al. (2011). The report that investigated the effects of N and K fertilization in *A. muelleri* suggested K fertilizer to be applied to the plants at 1 WAP to secure a baseline nutrient supply. However, this timing did not take into account the temporal variation in nutrient demand throughout the crop growth cycle. In contrast to the present findings which is supported by turnover point analysis, the K peak demand in konjac that solely depend on soil K content (T1) occurs later; between approximately 9-11 WAP depending on shading intensity. Application of K at 9-11 WAP coincides with the period of rapid vegetative expansion and maximum nutrient uptake, when K is most critical for maintaining osmotic balance, regulating stomatal conductance, and facilitating assimilate translocation (Xu et al., 2020).

More importantly, synchronizing fertilizer application with the phase of highest physiological demand enhances nutrient-use efficiency and sustains canopy performance during the subsequent corm bulking stage. Thus, while early application at 1 WAP secures a baseline nutrient supply, scheduling K application closer to 9 WAP provides potential targeted approach that aligns fertilizer availability with the temporal dynamics of nutrient demand in konjac, offering potential benefits for crop performance and resource efficiency.

CONCLUSIONS

In *Amorphophallus muelleri* planted using seed, the recommended shading rate is 70% since it enhances K uptake, growth, photosynthetic efficiency and yield while planting under direct sunlight is detrimental to the plants. The optimal K rate under 70% shading was between the range of 150 to 225 kg ha^{-1}. It was not recommended to fertilize beyond the rate of 225 kg ha^{-1} as it will potentially lead to potential K losses and less yield impact. The optimum time for K fertilization which can enhance K uptake efficiency under the recommended 70% shading rate is between 9-10 wk after planting.

Author contribution

Conceptualization: M.N.O.G., M.M.Y. Methodology: M.N.O.G., M.M.Y., A.S.A.S. Software: A.S.A.S., M.N.O.G. Validation: A.S.A.S. Formal analysis: A.S.A.S., M.N.O.G., M.M.Y. Investigation: M.N.O.G., M.M.Y., A.S.A.S. Resources: M.M.Y., J.N.J., A.M. Data curation: M.N.O.G., A.S.A.S., Z.B. Writing-original draft: M.N.O.G. Writing-review & editing: M.N.O.G., M.M.Y., A.S.A.S. Visualization: M.N.O.G., A.S.A.S. Supervision: M.M.Y., A.S.A.S., J.N.J., A.M. Project administration: M.M.Y. Funding acquisition: M.M.Y., J.N.J., A.M.

Acknowledgements

The authors would like to express their gratitude to Universiti Putra Malaysia (UPM) for the financial support provided through the Industrial Research Grant in collaboration with Ladang Konjak Ltd. (Vot No: 6300420) under the project title "Evaluation of Different Local and Imported Konjac Varieties for Growth, Yield Potential and Enhancing the Accumulation of Glucomannan in Konjac Grown at Two Different Locations". The authors further acknowledge the Malaysian Agricultural Research and Development Institute (MARDI) for granting study leave, and Yayasan Khazanah for providing financial assistance throughout the study period.

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