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Seed Scarification Improves Physiological Growth and Development of Bambara Groundnut (*Vigna subterranea*) Depending on Seed Coat Colour

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Abstract: This study was conducted to investigate the effect of scarification on bambara groundnut (*Vigna subterranea*) physiological growth and development and crop phenology. Bambara groundnut landrace seeds used in this study were characterized by seed coat colour (cream, light brown and brown). Seed scarification treatments were mechanical (sand paper) and chemical (sulphuric acid) scarification, while seeds that were not scarified served as a control. A completely randomized design with three replications was used. The parameters that were assessed were time to emergence, final emergence percentage, leaf number, chlorophyll content index (CCI), canopy diameter, plant height, chlorophyll fluorescence (F_v/F_m), photosynthetic performance index (*Pi*), time to flowering and time to senescence. CCI, leaf number and plant height were significantly ($p < 0.05$) influenced by seed coat colour, seed scarification treatments and their interaction thereof. Seed scarification treatment had a significant effect on CCI, leaf number and plant height. Generally, seed scarification improved plant overall performance than the control. Chemical scarification presented superior performance of bambara groundnut growth and development. Light brown seeds produced plants with superior overall performance, having superior emergence, CCI, leaf number, and early flowering and senescence. Light brown seeds were followed by cream seeds in terms of superiority of plant performance, having produced plants with superior canopy diameter, plant height and *Pi*. Therefore, bambara groundnut farmers and researchers can successfully use scarification to improve its physiological growth and attain earlier phenological stages, hence maturity. At the same time, light brown seeds should be selected for cultivation to give the best plant performance.

Key words: Canopy cover, chlorophyll, plant development, plant growth, photosynthesis.

1. Introduction

There are many challenges currently hampering food and nutrition security including climate change and variability, increasing competition for water, loss of productive land and competition for available land use [1, 2]. This challenge is exacerbated by the high demand for food due to extremely increasing population and increased affluence in developing countries [3]. The world population is expected to be about 8.6 billion in 2030, 9.8 billion in 2050 and 11.2 billion by 2100 [4]. At the same time, there is a need for ~60% intensification of food production by 2050 to meet the required food production increments [5]. In addition to the need for increasing crop production is a need for food diversification to ensure food and nutrition security. This should include the exploration of crops that have been neglected but have great potential for food security such as bambara groundnut which is a high protein legume.

Bambara groundnut as a drought-tolerant crop [6] that is less demanding from the soil can grow in most marginal environments [7]; thereby can play an important role in meeting high yields to fulfil food security. The crop's ability to adapt to marginal conditions is attributed to its multiple genotypes within many landraces which increase tolerance to

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biotic and abiotic stresses [8]. Moreover, bambara groundnut being a highly nutritious crop [9, 10] has the potential to provide nutrition security especially for malnourished societies from the underdeveloped world. In addition to food and nutrition security, the crop can play a vital role in diversifying food options and supplement famous legume and cereal food options. However, the crop still faces a challenge of poor physical seed quality such as hard seededness and physical dormancy leading to erratic plant stands and subsequently poor yield. Hard seed coat and dormancy in bambara groundnut may hamper radicle penetration through the seed coat resulting in poor and delayed germination, hence poor emergence.

Despite these challenges faced by most legume seeds including bambara groundnut, the agricultural systems still have the responsibility to produce and distribute high quantities of quality food products. In agricultural food production, seeds are the first basic critical input whereby the success of other inputs depends on seed quality [11, 12]. Crop performance and yield potential are mainly influenced by the quality and status of seeds that are propagated. Therefore, improving seed quality and overcoming seed dormancy through scarification may lead to the success of crop production to high standability, yields and quality produce. However, the success of scarification on plant growth performance and biomass accumulation has never been tested before. Most research on seed invigoration including scarification focuses on seed vigour, germination vigour and seedling establishment vigour without taking it further to plant growth, development, biomass production, maturity and yield. Therefore, exploring plant growth and development performance of bambara groundnut in response to seed scarification will contribute not only to the body of knowledge where there is a gap but also to the improvement of one of the under-researched and underutilised crops.

This research aimed to evaluate the effect of seed scarification on plant growth physiology and dry matter production of bambara groundnut. Plant growth and development were associated with seed mineral and nutritional content of the sown seed. The objectives of the study were to assess crop stand establishment, growth physiology, phenology and seed mineral and nutritional content of bambara groundnut in response to seed scarification depending on seed coat colour.

2. Materials and Methods

2.1 Plant Material and Experimental Design

Landrace seeds of bambara groundnut were donated by farmers from Pongola, North of KwaZulu-Natal, South Africa (27°23′3″ S; 31°37′1″ E). Seeds from the same landrace were characterized according to seed coat colour: cream, light brown and brown (Fig. 1). The seeds were checked for viability according to tetrazolium chloride test based on International Seed Testing Association (ISTA) rules [13] before use in this research.

Seeds were imposed to scarification before planting in pots located in the greenhouse. The scarification treatments were T_1—no scarification (control), T_2—mechanical scarification and T_3—chemical scarification. Mechanical scarification was carried out using 150-fine sandpaper with which the seeds were scraped 10 times on four circumference regions. Chemical scarification was carried out using 95%-99% undiluted sulphuric acid according to Bonner *et al*. [14]. Seeds were completely immersed in the beakers containing the acid for 10 min at room temperature (25 °C). After 10 min the seeds were washed thoroughly for 5-10 min in running distilled water. The treatment structure was a combination of three seed coat colours and three scarification treatments, with three replications. The experimental design was completely randomised design (CRD) replicated three times. The treated seeds were planted in the greenhouse (27/15 °C day/night; 65% RH and natural day length) at the University of KwaZulu-Natal,

Fig. 1 Landrace seeds of bambara groundnut (*Vigna subterranea* L.) characterized according to seed coat colour (cream, light brown and brown).

Table 1 Soil chemical analysis for crop production related nutrient elements.

pH (KCl)	Org. C (%)	N (%)	P (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	Zn (mg/L)	Mn (mg/L)	Cu (mg/L)
4.9	1	0.08	64	190	1,535	375	8.6	32	4.1

Pietermaritzburg (29°37′33″ S; 30°24′16″ E) using 10 L (30 cm diameter and 28 cm depth) plant pots filled with 8 kg of soil. The soil used in the current research was analysed by the Department of Agriculture and Environmental Affairs (Soil Analytical Services, Pietermaritzburg) (Table 1).

2.2 Seed Nutritional and Mineral Content

Seed nitrogen (N), carbon (C) and sulphur (S) were measured using Leco (TruMac, USA) with 0.2 g sample of bambara groundnut seed tissue powder according to Gazulla *et al*. [15]. Protein content was calculated from N using the protein factor of 6.25. Calcium (Ca), copper (Cu), iron (Fe), potassium (K), magnesium (Mg), sodium (Na) and phosphorus (P) in the seed tissue were determined using flame atomic absorption spectrophotometry according to standard soil testing methods [16]. Total mineral content was calculated as the sum total of all the minerals measured in this study including Ca, Cu, Fe, K, Mg, Na and P.

2.3 Agronomic Management

The plants were watered manually three times a week at 75% field capacity before flowering and two times after flowering. Weeds were controlled manually upon appearance. Powdery mildew that infested some plants was controlled using benomyl (benzimidazole 500 g/kg) and insects were controlled using mercaptothion (organophosphate 500 g/L) and chlorpyrifos (organophosphate 480 g/L).

2.4 Data Collection

Emergence rate and final emergence percentage were monitored from one week after sowing the seeds. Plant growth and development parameters were evaluated weekly and averages were recorded after measuring three plants. The above soil plant part was measured for plant height. The measurement started from the soil surface to the leaves at the tip of the plant, using a measuring ruler. Canopy diameter was measured on the canopy cover at three points using a ruler and averaged. Leaf number was counted based on fully expanded green leaves. Surface leaf area was measured with a measuring ruler where leaf length and breadth were measured from three mature leaves of the same plant and averaged.

Chlorophyll content index (CCI) was measured using SPAD-502 Plus (Konica Minolta, Japan) portable chlorophyll meter from three fully expanded leaves from above canopy position receiving maximum light and averages were recorded. Pocket PEA chlorophyll fluorimeter (Hansatech Instruments, England) was used to measure chlorophyll fluorescence (F_v/F_m) and photosynthetic performance index (*Pi*) from fully expanded leaves. Plant phenology in terms of flowering and senescence was established.

2.5 Statistical Analysis

Data collected were subjected to analysis of variance (ANOVA) applying Duncan's multiple range test using GenStat® version 18 (VSN International, United Kingdom) at $p \leq 0.05$ level of significance.

3. Results and Discussion

3.1 Rate of Emergence and Final Emergence Percentage

3.1.1 Interaction between Seed Coat Colour and Seed Scarification Treatments

There were no significant differences ($p > 0.05$) in the final emergence percentage among all treatment combinations. These results contradicted those of Miya and Modi [17]. However, it is important to note that all treatment combinations had 100% final emergence except for cream seeds from the control (non-scarified seeds) which had 67% final emergence (results not shown). On the other end, seed coat colour, scarification and their interaction thereof significantly influenced ($p < 0.05$) time to emergence. It took the planted seeds two weeks after planting (WAP) for the first emergence to occur from all seed coat colours in the control treatment, as well as light brown and brown seeds from chemical scarification, similarly. Cream seeds from chemical and mechanical scarified seeds similarly had a relatively poor rate of emergence of 3 WAP (Fig. 2). These results were in line with Mabhaudhi *et al.* [6] who also reported that it took 21 d for bambara groundnut landrace seeds to germinate; while on the other end Sesay and Yarmah [18], and Sinefu [19] reported slow emergence of bambara groundnut landraces which took up to 35 d and 28 d after planting, respectively.

3.1.2 The Effect of Seed Coat Colour on Time to Emergence

Seed coat colour had a significant influence on time to emergence. Brown seeds took the shortest time to emerge, followed by light brown and then cream seeds (results not shown). Dark pigmented seeds (brown and light brown) had vigorous emergence to cream seeds.

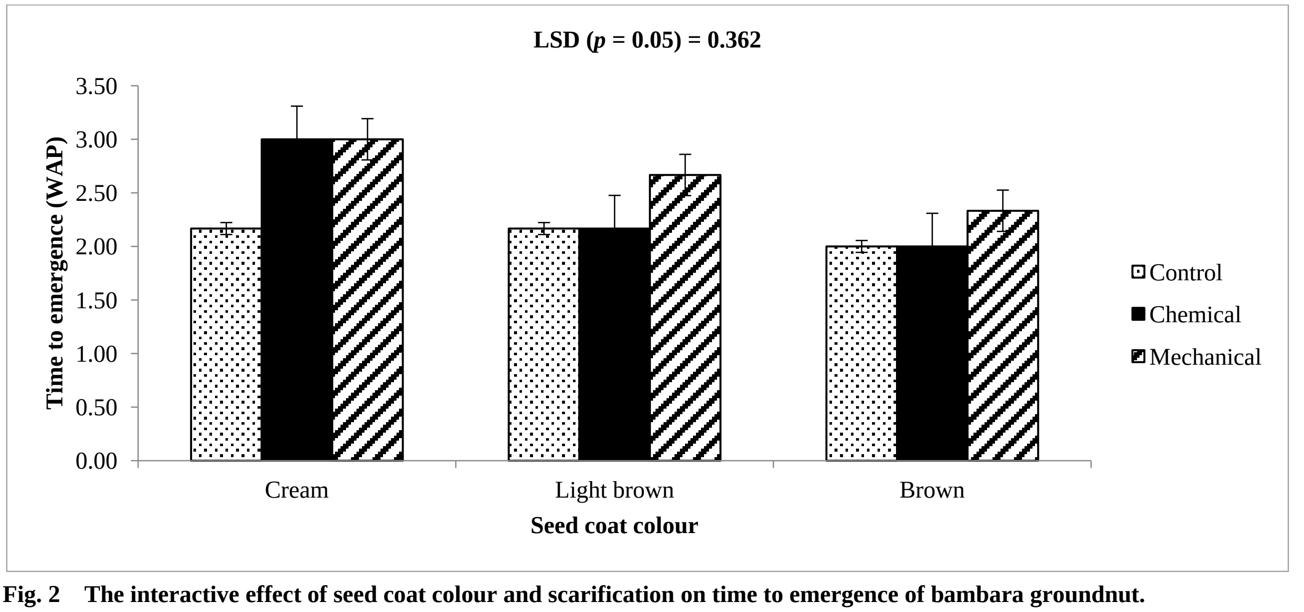

Fig. 2 The interactive effect of seed coat colour and scarification on time to emergence of bambara groundnut.
WAP: weeks after planting.

These results corroborated with Miya and Modi [17], Sinefu [19], Mabhaudhi and Modi [20], Zulu and Modi [21], Mbatha and Modi [22], and Mabhaudhi [23]. Therefore, it can be concluded from this study that darker seeds were able to sufficiently absorb water, nutrients and oxygen which enhanced hasty germination and subsequently emergence compared to cream seeds. This may be ascribed to dark pigmented seeds having high levels of phenolic compounds [24] which is characteristic of darker seeds. Phenolics have protective antioxidant properties that counteract seed deterioration and damage that may occur during initial water imbibition. The accompanying antioxidant properties also maintain structural and functional integrity of cells [25].

Seeds contain organic and mineral nutrients that supplement early soil supply and nurture germination, seedling establishment, root and shoot development before young seedling can photosynthesize and develop root hairs [26, 27] for oxygen, water and nutrient acquisition. Seeds that exhibited superior emergence in this study including light brown were characterised by having the highest N (0.251%), S (0.251%) and proteins (18.583%). On the other hand, brown seeds had the highest C (47.576%) content and C:N ratio (16.338). These darker seeds rapidly germinated due to high reserves and high seed quality. Among seed reserve contents, N and C are reliable high seed quality indicators [28]. C and N compounds supported rapid early growth as they provide immediate growth needs. Moreover, the absorption and utilization of other elements such as K and P is also encouraged by N which ultimately controls the overall plant growth [29, 30].

3.2 Chlorophyll Content Index (CCI)

3.2.1 The Effect of Seed Scarification Treatments on CCI

Seed scarification treatments, seed coat colour and their interaction thereof significantly affected ($p < 0.05$) leaf CCI. Mechanical scarification resulted in the production of plants with greater leaf CCI (49.6) which was significantly higher than that of plants from the control (48.3) and chemical scarification (46.7) (Fig. 3a). Mg was found in highest quantity 1,493.506 (mg/L) in mechanically scarified seeds (Table 2) which produced plants with high CCI. Mg is a crucial part of chlorophyll which in turn is important for photosynthesis [31, 32]. Therefore, Mg from the seeds played an important role in the early formation of chlorophyll contentment in the leaves which was high throughout the plants that were sown from mechanically scarified seeds.

3.2.2 The Effect of Seed Coat Colour on CCI

With respect to seed coat colour, brown (49.2) and light brown (49.3) seeds produced plants with statistically similar and higher leaf CCI compared to cream seeds (46.1) (Fig. 3b). Chlorophyll located in the chloroplasts of green plant cells occurs in the form of chlorophyll *a* and *b* that serves as photoreceptors during photosynthesis in plants [33]. Therefore, plants with higher leaf CCI such as those produced by light brown seeds and mechanically scarified seeds were better able to absorb greater light energy that increased CO_2 assimilation for adequate photosynthesis. These plants characteristically have higher N content in their leaves essential for the regulation of photosynthesis [34-36]. N content of light brown seeds was the highest at 2.973% compared to other seed coat colours. These seeds also had the highest amounts of Fe (21.550 mg/L) and S (0.251%) (Table 2). Fe is known to maintain chloroplast function as well as structure [37] that housed chlorophyll in the leaves. S also plays an essential role in chlorophyll synthesis [38].

Young leaves from developing seedlings and plants of bambara groundnut attained mineral contents such as N, Fe, Mg and S from the seeds for initial chlorophyll production to photosynthesise and maintain the photosynthetic apparatus before the leaves are able to provide reserves and sustain themselves. All these mineral reserves abundant in the sown light brown seeds and mechanically scarified

Table 2 Seed mineral and nutrient content descriptions based on seed analysis based on standard soil testing methods [16].

Seed coat colour	Scarification	C	N	S	Protein	C:N	Ca	Fe	K	Mg	Na	P	Total mineral elements
				%						mg/L			
Cream	Control	47.403	2.854	0.213	17.835	16.612	922.600	18.856	12,463	1,620.631	116.191	2,580.785	17,748
	Mechanical	47.139	2.957	0.183	18.484	15.939	692.318	24.016	12,546	1,499.566	144.011	2,641.283	17,565
	Chemical	47.251	2.951	0.184	18.441	16.014	713.297	19.462	11,689	1,266.840	142.886	2,804.686	16,659
Light brown	Control	47.934	2.981	0.178	18.631	16.080	772.771	21.406	10,226	1,296.828	108.659	2,630.358	15,073
	Mechanical	47.474	2.882	0.200	18.014	16.471	611.425	20.051	12,626	1,510.664	125.769	2,815.411	17,732
	Chemical	47.319	2.874	0.177	17.963	16.464	620.350	23.193	13,008	1,522.439	144.746	2,855.702	18,195
Brown	Control	47.599	3.037	0.270	18.980	15.674	655.466	20.456	12,523	1,456.833	111.844	2,823.091	17,610
	Mechanical	46.903	2.902	0.266	18.140	16.160	682.060	15.368	10,613	1,470.288	101.356	2,768.750	15,670
	Chemical	47.374	2.980	0.216	18.628	15.895	680.939	23.976	12,706	1,519.911	133.614	2,718.782	17,804

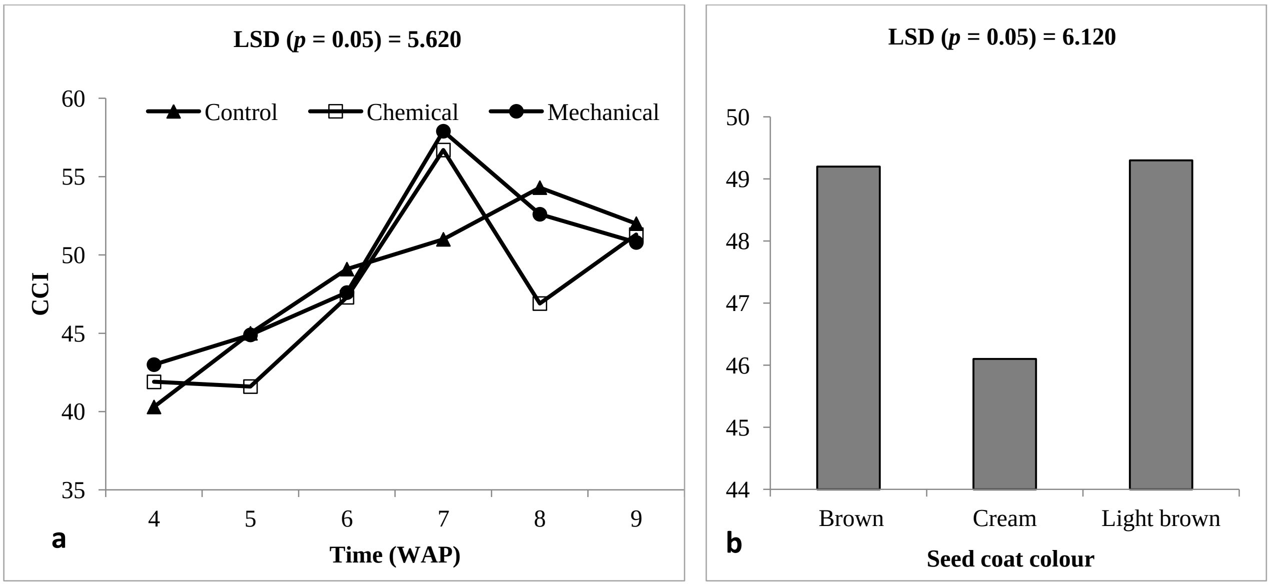

Fig. 3 Chlrophyll content index (CCI) of bambara groundnut in response to seed scarification treatments (a) depending on seed coat colours (b).

WAP: weeks after planting.

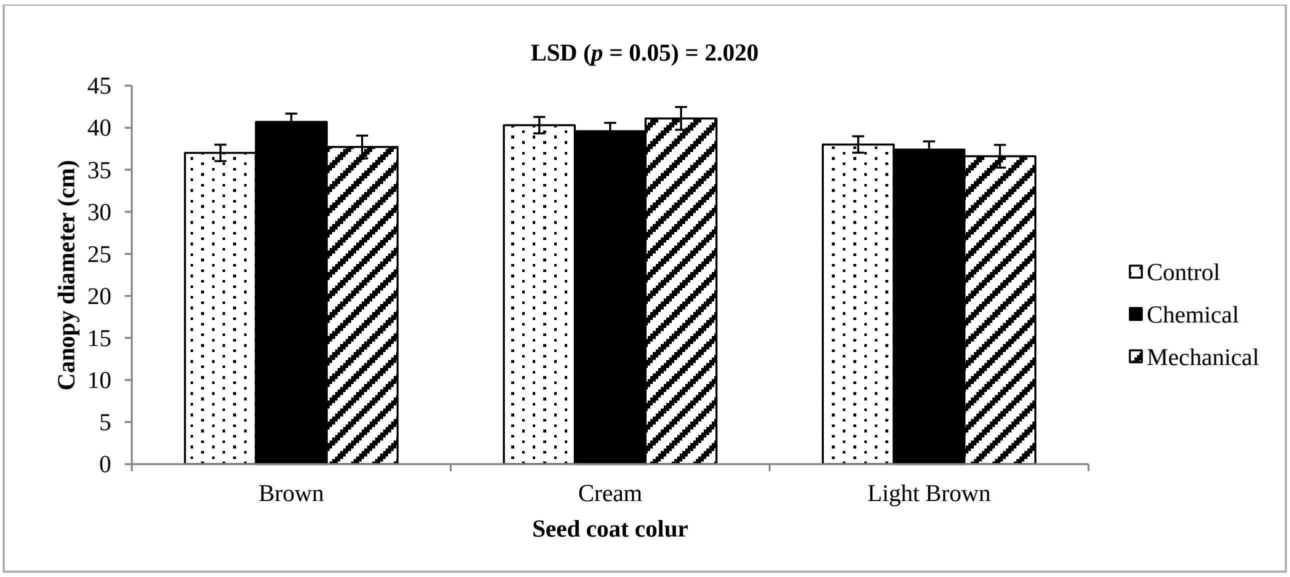

Fig. 4 The response of bambara groundnut canopy diameter to seed scarification depending on seed coat colours.

seeds played an important role in providing early nutrition and structural components for first leaves and their development. These seed reserves were vital for physiological changes in the plant and kick-starting the level of vigour which may be carried over to all plant stages.

3.3 Canopy Diameter

Seed coat colour and the interaction between seed coat colour and scarification had significant ($p < 0.05$) effect on canopy diameter. Cream seeds that were mechanically scarified produced plants with the highest canopy cover (41.1 cm) which was significantly similar to plants from brown seeds that were chemically scarified (40.7 cm) and cream seeds from the control (40.3 cm). Light brown seeds having mechanical (36.6 cm) and chemical (37.4 cm) scarification, as well as brown seeds from the control

(37.0 cm), produced the lowest and statistically similar plant canopy cover (Fig. 4).

Canopy diameter, in addition to other canopy traits such as leaf number, leaf area and plant height is important plant growth and development traits that serve as main determinants of photosynthesis efficiency of crops in the canopy. These traits determine photosynthetic efficiency since they are associated with plant competition for light energy used for photosynthesis. This is consequently important for biomass accumulation and yield production. Hence, high yielding landraces are characterised by large and rapidly growing canopies, among other things. This is attributed to the fact that large canopies have high light interception resulting in optimum photosynthesis which supports biomass and yield production. Moreover, it is important to note that canopy traits change during different phenological stages due to changes in source-sink relationships. During early vegetative plant stages, the expanding canopy sustains lower photosynthesis rate and energy consumption, while assembling structural plant components.

3.4 Leaf Scores

3.4.1 The Interactive Effect of Seed Coat Colour and Scarification on Leaf Scores

Seed coat colour, seed scarification and their interaction thereof had significant ($p < 0.05$) effect on leaf number. The interaction of chemical scarification and light brown seeds produced plants with many leaves which were 35.71% higher than leaves from plants that were produced by mechanically scarified cream seeds (Fig. 5). Moreover, light brown chemically scarified seeds had the highest amount of total minerals (18,195 mg/L), K (13,008 mg/L), Na (1,036.8 mg/L) and P (2,856 mg/L) (Table 2). These mineral reserves initiated vigorous seedling growth with vigour longevity which influenced crop's performance throughout its life cycle while having many leaves in the canopy.

K, Na and P are all responsible for plant growth and development in the form of biomass accumulation in plants which was directed toward the leave in this case [39-41]. Leaves as indicators of plant growth and development were influenced by initial available K, Na and P concentrations for better performance. The promotion of leaf growth and development by K in plants may be attributed to this element being able to control the stomatal opening and closing [42] which is essential for the photosynthesis process, water relations, enzyme activation and transportation of photosynthates [39]. On the other end, Na that induced leaf growth and development was due to the fact that this element is an osmoticum for cell enlargement, which occurred in the leaves in this case. Additionally, the rate of nutrient use efficiency was improved by this element [40] which improved leaf growth and development. Furthermore, P influenced metabolic processes, translocation and energy transference (adenosine triphosphate (ATP)) which is required for photosynthesis [42]. These ultimately enhanced plant production as well as leaf growth and development [41].

3.4.2 The Effect of Seed Coat Colour on Leaf Scores

With regards to seed coat colours, light brown seeds produced plants with the highest leaf number (18) followed by brown (17) and cream (16) seeds, respectively (results not shown). These results were in line with Sinefu *et al*. [19]. These results may be attributed to light brown seeds in this study having the highest N, P and protein content with 2.973%, 2,767.157 mg/L and 18.583%, respectively.

N, which can also be derived from proteins, is one of the key elements of crop production [40] that facilitate and enhance rapid plant growth [29, 30] and ultimately productivity which may be ascribed to high photosynthetic rate that is promoted by this element [43]. This element improves several biochemical and physiological processes in plants and promotes vegetative plant growth and development in the form

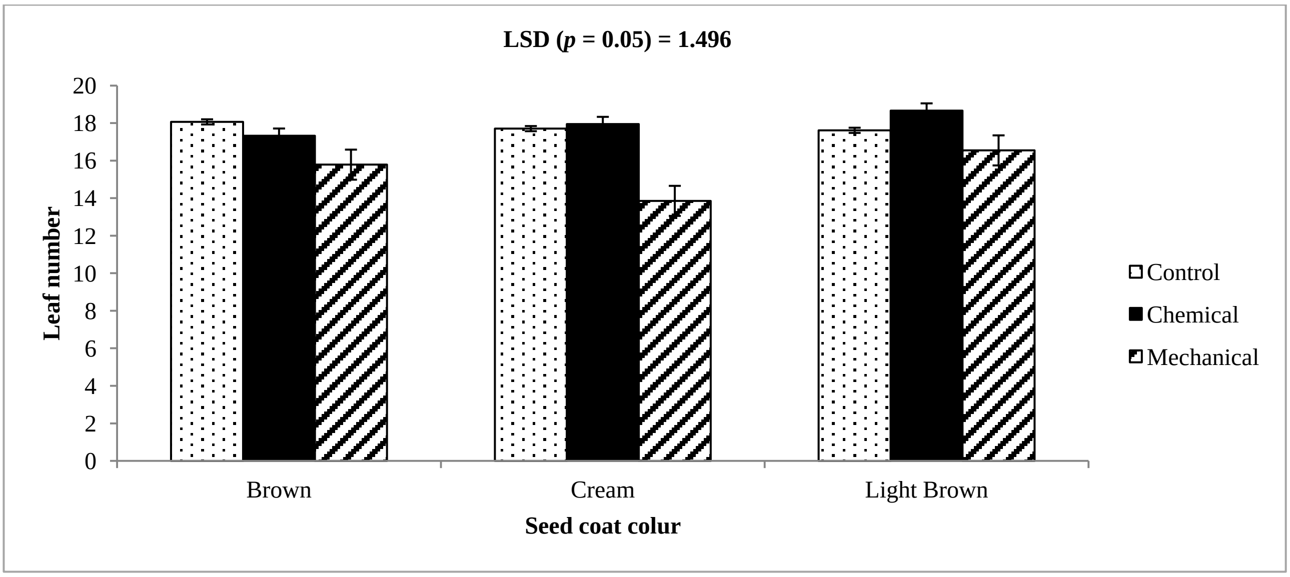

Fig. 5 The interactive effect of seed coat colour and seed scarification on bambara groundnut leaf number.

of leaves and stems as well as root growth. Moreover, N increases the absorption and use of other nutrients such as P and K [29, 30]. In addition to growth promotion by N, P is also essential for various processes in plants such as energy generation, enzyme activation, nucleic acid synthesis, N fixation, photosynthesis, glycolysis, respiration, membrane synthesis and stability, and carbohydrate metabolism [44]. All these plant activities are vital for plant growth and development, which makes P a very important element for overall plant growth and development [45].

3.5 Plant Height

3.5.1 The Interactive Effect of Seed Coat Colour and Scarification on Plant Height

Seed coat colour, scarification and their interaction thereof had significant ($p < 0.05$) effect on plant height. The interaction of cream seeds and chemical scarification produced the 25.25% significantly tallest plants compared to the shortest plants sown from light brown mechanically scarified seeds (Fig. 6).

3.5.2 The Effect of Seed Coat Colour on Plant Height

Brown (23.60 cm) and cream seeds (23.70 cm) produced plants with higher but not significantly different plant heights. These plants were significantly different to plants from light brown seeds (22.00 cm) which produced the shortest plants (results not shown). Sinefu [19] also reported significantly tallest plants from white seeds followed by brown. These results corroborate in having taller plants being produced by light pigment seeds compared to dark pigmented seeds. Cream seeds in this research were able to support taller plant height given that they had the highest amounts of Ca (776.071 mg/L) and total mineral nutrition (17,324 mg/L) to support initial growth. Ca activated important enzymes for cell division, cell growth and elongation [46] which ultimately enhances plant growth and development [47] which was directed more towards the height in this research. Ca was also able to improve the uptake of nutrients, while it enhanced plant tissue and cell wall integrity and ultimately contributed to normal root system development [46]. Vigorous root development results in optimum absorption of water and nutrients from the soil for further vigorous whole-plant growth and development throughout the plant's life cycle. Hence the height of bambara groundnut plants was enhanced in this study.

On the other end, brown seeds had more C (47.576%) and a high ratio of C:N (16.338) (Table 2) which contributed to vigorous plant growth and development. C which was the highest in superior brown seeds is the basic component of carbohydrates, proteins, lipids and nucleic acids. These molecules are important for cell elongation and cell functioning hence plant development and growth. Therefore, it can be concluded that the abundance of C was accompanied by these molecules which in turn improved plant height of bambara groundnut in this study.

3.5.3 The Effect of Seed Scarification on Plant Height

Seeds that were chemically scarified (24.00 cm) and seeds from the control (23.30 cm) produced taller plants with statistically similar plant heights. However, these plants were significantly different from plants produced by mechanically scarified seeds (22.10 cm) which produced the shortest plants. Seeds that were chemically scarified having produced plants with many leaves and the tallest plants may be attributed to the highest amount of P (2,793.057 mg/L), and total minerals (17,552 mg/L) (Table 2) that are important in supporting the overall plant growth and development.

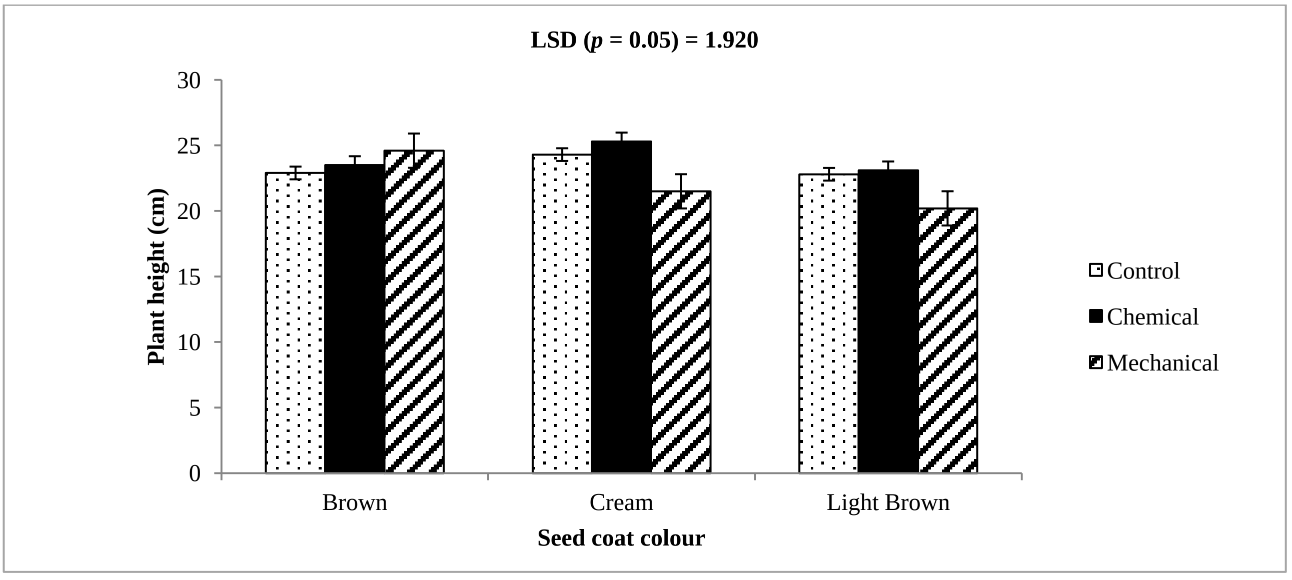

Fig. 6 The interactive effect of seed coat colour and seed scarification on bambara groundnut height.

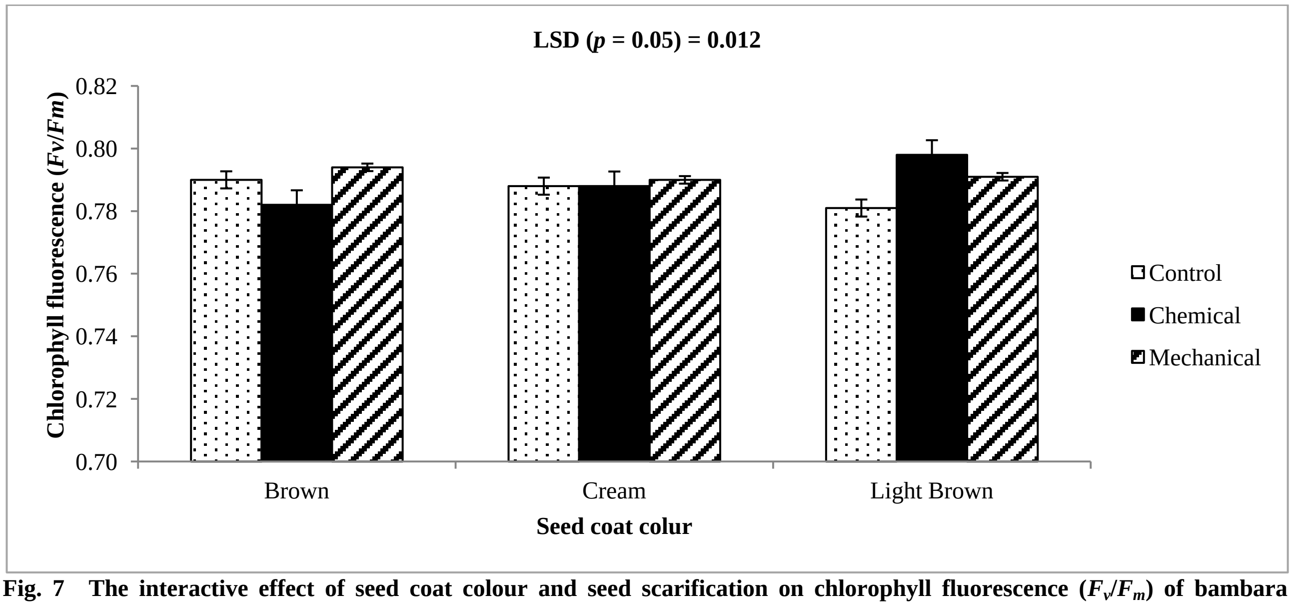

Fig. 7 The interactive effect of seed coat colour and seed scarification on chlorophyll fluorescence (F_v/F_m) of bambara groundnut.

3.6 Chlorophyll Fluorescence (F_v/F_m)

The interaction of seed coat colour and seed scarification treatments significantly ($p < 0.05$) influenced the chlorophyll fluorescence of plants in the current study. However, chlorophyll fluorescence showed no significant response to seed coat colour factor and seed scarification treatments. Plants produced from light brown seeds that were chemically scarified had the highest chlorophyll fluorescence of 0.798, while light brown seeds from the control produced plants with the lowest fluorescence of 0.781 (Fig. 7).

Chlorophyll fluorescence measures the photosystem II (PSII) activity in plant physiology to understand the PS mechanism and response of plants to environmental changes [48]. Light energy absorbed by chlorophyll molecules may be used for photosynthesis (photochemistry), while excess energy can be dissipated as heat or reemitted as light (fluorescence) [35, 48]. Valuable information regarding the heat dissipation and quantum efficiency of photochemistry may be derived from the yield of chlorophyll fluorescence emission. A transient increase in chlorophyll fluorescence due to the decrease of electron carriers in the thylakoid membrane occurs upon application of sufficient light to drive photosynthesis to a leaf after dark adaptation. A maximum fluorescence is thereafter induced upon closing reaction centres after applying a saturating pulse to a dark-adapted leaf. This measures the level of stress in leaves [48].

Chlorophyll fluorescence (F_v/F_m) is one of the indicators for photosynthetic regulation in plants including health and integrity of the photosynthetic apparatus within a leaf [49]. Chlorophyll fluorescence intensity is related to the amount of excited chlorophyll molecules as a measure of leaf photosynthetic efficiency [35]. In the current research, plants produced from light brown seeds that were scarified chemically had the highest chlorophyll fluorescence. This indicates that plants produced from these seeds were able to use the photosynthetic resources more efficiently than other treatments. These plants had F_v/F_m higher than 0.790 which is considered to give a good indication of photosynthetic efficiency [50, 51], whereas F_v/F_m lower than 0.720 shows less efficiency [51]. In most plants, F_v/F_m is optimum at 0.83 which relates to the maximum photosynthesis quantum yield [52] except in plants exposed to stress responding with photo-inhibition [53].

There is a direct association between F_v/F_m ratio and quantum efficiency which is a good stress measure [54]. It can be concluded from the results of this study that although scarification (mechanical and chemical) corrodes the seed coat it does not impose any detrimental carry-over effect that hinders the photosynthetic process to produce stressed plants. Although the plants that are reported in this study are evidently not stressed, plants from mechanically scarified seeds were better adapted while seed from the control produced plants that were relatively less adapted. This may be an indication that plants from scarified seeds were vigorous throughout all stages of growth and development from germination, to the emergence and ultimately vigorous stands with efficient photosynthesis.

3.7 Performance Index (Pi)

Bambara groundnut plant weekly performance responded significantly ($p < 0.05$) to seed coat colour effect with regards to *Pi*, with cream seeds being superior (Fig. 8). Seed scarification and the interactive effect of seed coat colour and seed scarification treatments had no significant effect on *Pi* of the produced bambara groundnut plants. However, it is important to note that consistently with most plant parameters measured in this study, chemically scarified seeds and light brown seeds that were chemically scarified produced plants that were superior with respect to *Pi* (results not shown).

Emergence, leaf number, plant height and chlorophyll fluorescence agreed with the response of *Pi*. *Pi* of bambara groundnut in this research played a vital role in enhancing these plant parameters, except emergence which is not associated with photosynthesis since *Pi* directly impacts sunlight conversion in the chloroplast.

It can be concluded that CO_2 assimilation and light-harvesting for photosynthesis was efficient in plants produced from light brown seeds that were chemically scarified and; chemically scarified seeds. This, in turn, promoted leaf development, plant height and chlorophyll fluorescence and ultimately plant productivity.

3.8 Crop Phenology-Flowering and Senescence

There was no significant difference in all treatment combinations with regards to flowering in bambara

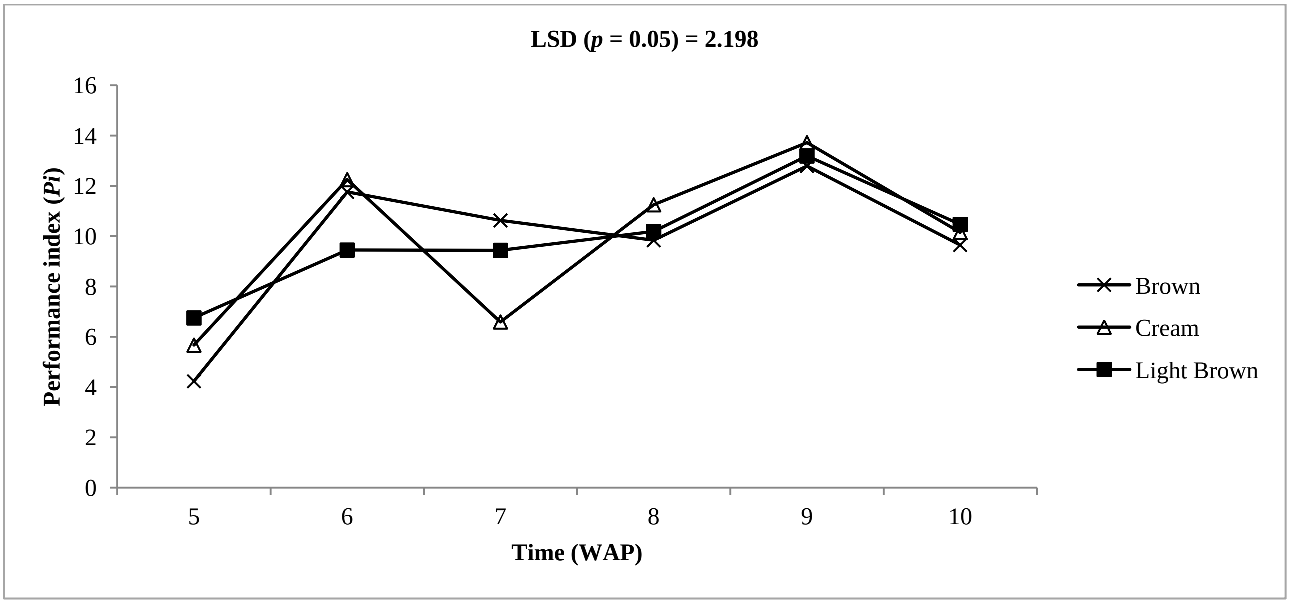

Fig. 8 The effect of seed coat colour on weekly performance index (*Pi*) of bambara groundnut.
WAP: weeks after planting.

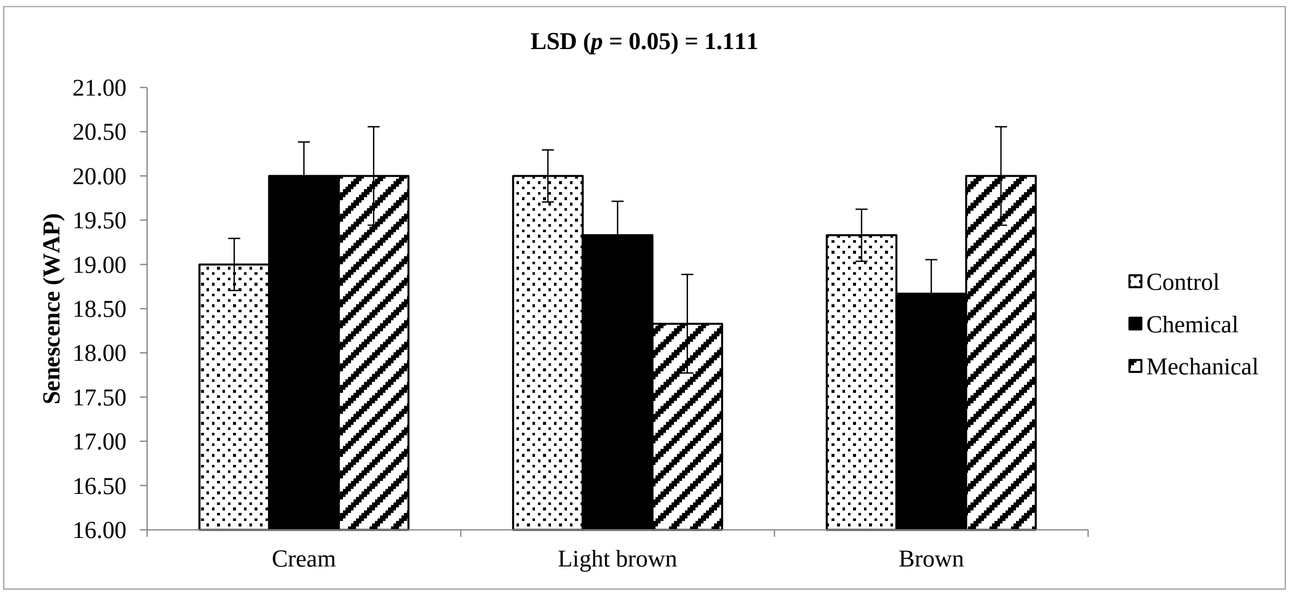

Fig. 9 The interactive effect of seed coat colour and scarification treatments on bambara groundnut senescence.
WAP: weeks after planting.

groundnut. Seed coat colour and scarification had no significant effect on senescence in bambara groundnut. However, the interaction between seed coat colour and scarification significantly influenced senescence in bambara groundnut. Plants sown from light brown seeds that were scarified chemically and mechanically, as well as brown seeds from the control and chemical scarification, took the shortest time to attain flowering (7 WAP) while the rest of the other treatments took 8 WAP. Later on, during the plant's life cycle, plants produced by light brown seeds with mechanical scarification took the shortest time to senescence which occurred 18 WAP. The treatments that produced plants with the latest senescence which took 20 WAP were cream seeds from chemical and mechanical scarification, light brown seeds from the control, and brown seeds from mechanical scarification (Fig. 9).

The rate of senescence may indicate that leaf and leaf area development of plants were hasty such as that of plants produced by light brown seeds with mechanical scarification. These plants were proceeded through all plant growth stages quickly, which led to early senescence (maturity) of the canopy. The canopy cover changes from full canopy cover to a reduced canopy cover during senescence.

Those plants that flowered and senesced earlier basically had faster growth and development rate. Light brown seeds that were mechanically scarified consistently had faster maturity with regards to flowering and senescence. These plants had adequate photosynthesis to be able to accumulate sufficient photosynthates that support flower development. Early plant growth and development may be advantageous for plants to escape any potential stress conditions during the plant's life cycle.

4. Conclusions

This research was conducted to evaluate the effect of seed scarification on plant growth physiology, development and crop phenology of bambara groundnut. The results showed that bambara groundnut growth, development, physiology and phenology are influenced by scarification and seed coat colour and their interaction. Seed scarification treatments both improved plant performance of bambara groundnut with chemical scarification being the best treatment. Light brown seeds having produced plants with superior performance were the best seed coat colour selection. Therefore, producers can use seed scarification to improve bambara groundnut emergence, physiological growth and development as well as plant phenology (maturity). Bambara groundnut farmers should be discriminating with regards to seeds, sow and select light brown seeds for best sowing. All measured parameters in this study may serve as important markers of plant performance, vigour and photosynthetic efficiency, while seed coat colour may be used as a marker for seed quality. The results of this research may be used to enhance stand establishment and promote better biomass accumulation and maturity in bambara groundnut.

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References

[1] Gregory, P. J., Ingram, J. S. I., and Brklacich, M. 2005. "Climate Change and Food Security." *Philosophical Transactions of the Royal Society of London. Series B Biol. Sci*. 360: 2139-48.

[2] Kahane, R., Hodgkin, T., Jaenicke, H., Hoogendoorn, C., Hermann, M., Dyno Keatinge, J. D. H., and D'Arros Hughes, J. 2013. "Agrobiodiversity for Food Security, Health and Income." *Agron. Sustain. Dev*. 33: 671-93.

[3] Weinzettel, J., Hertwich, E. G., Peters, G. P., Steen-Olsen, K., and Galli, A. 2013. "Affluence Drives the Global Displacement of Land Use." *Global Environ. Change* 23: 433-8.

[4] United Nations, Department of Economic and Social Affairs, Population Division. 2017. "World Population Prospects: The 2017 Revision, Key Findings and Advance Tables." Working Paper No. ESA/P/WP/248.

[5] Alexandratos, N., and Bruinsma, J. 2012. "World Agriculture towards 2030/2050: The 2012 Revision." Accessed August 2, 2016. http://www.fao.org/docrep/016/ap106e/ap106e.pdf.

[6] Mabhaudhi, T., Modi, A. T., and Beletse, Y. G. 2013. "Growth, Phenological and Yield Responses of a Bambara Groundnut (*Vigna subterranea* L. Verdc.) Landrace to Imposed Water Stress: II. Rain Shelter Conditions." *Water SA* 39: 191-8.

[7] Swanevelder, C. J. 1998. "Bambara Groundnut—Food for Africa (*Vigna subterranea*—Bambara Groundnut)." Agricultural Research Council and National Department of Agriculture, Pretoria, South Africa.

[8] Massawe, F. J., Mwale, S. S., Azam-Ali, S. N., and Roberts, J. A. 2005. "Breeding in Bambara Groundnut (*Vigna subterranea* (L.) Verdc.): Strategic Considerations." *Afri. J. Biotechn*. 4: 463-71.

[9] Linnemann, A. R. 1990. "Cultivation of Bambara Groundnut in Western Province, Zambia, Report of a Field Study." *Trop. Crop. Comm*. 16: 1-19.

[10] Ijarotimi, S. O., and Esho, R. T. 2009. "Comparison of Nutritional Composition and Anti-nutrient Status of Fermented, Germinated and Roasted Bambara Groundnut Seeds (*Vigna subterranea*)." *Brit. Food J*. 111: 376-86.

[11] Akinnuoye-Adelabu, D. B., and Modi, A. T. 2017. "Effect of Planting Date and Harvesting Stage on Seed Quality of 'SC 701' Maize under Small-Scale Farming Conditions." *Seed Sci. Technol*. 2: 368-82.

[12] Parimala, K., Subramanian, K., Mahalinga Kannan, S., and Vijayalakshmi, K. 2013. "A Manual on Seed Production and Certification." Accessed April 27, 2016. http://agritech.tnau.ac.in/seed_certification/pdf/A%20Manual%20on%20Seed%20Production%20and%20Certification.pdf

[13] International Seed Testing Association (ISTA). 2012. "International Rules for Seed Testing." Presented at the ISTA Annual Meeting 2011, Glattbrugg, Switzerland.

[14] Bonner, F. T., McLemore, B. F., and Barnett, J. P. 1974. "Pre-sowing Treatment of Seed to Speed Germination." In *Seeds of Woody Plants in the United States*. Washington, D.C.: United States Department of Agriculture, 126-35.

[15] Gazulla, M. F., Rodrigo, M., Orduña, M., and Gómez, C. M. 2012. "Determination of Carbon, Hydrogen, Nitrogen and Sulfur in Geological Materials Using Elemental Analysers." *Geostand Geoanal Res*. 36 (2): 201-17.

[16] The Non-affiliated Soil Analysis Work Committee. 1990. *Handbook of Standard Soil Testing Methods for Advisory Purposes*. South Africa: Soil Science Society of South Africa.

[17] Miya, S. P., and Modi. 2017. "Overcoming the Physical Seed Dormancy in Bambara Groundnut (*Vigna subterranea* L.) by Scarification: A Seed Quality Study." *J. Agr. Sci. Tech B* 7: 13-24.

[18] Sesay, A., and Yarmah, A. 1996. "Field Studies of Bambara Groundnut in Sierra Leone." In *Proceedings of the International Bambara Groundnut Symposium*, University of Nottingham, UK, July 23-25, 1996, 45-60.

[19] Sinefu, F. 2011. "Bambara Groundnut Response to Controlled Environment and Planting Date Associated Water Stress." M.Sc. thesis, University of KwaZulu-Natal.

[20] Mabhaudhi, T., and Modi, A. T. 2010. "Early Establishment Performance of Local and Hybrid Maize under Two Water Stress Regimes." *S. Afri. J. Plant & Soil* 27: 299-304.

[21] Zulu, N. S., and Modi, A. T. 2010. "A Preliminary Study to Determine Water Stress Tolerance in Wild Melon (*Citrillus lanatus* L.)." *S. Afri. J. Plant & Soil* 27: 334-6.

[22] Mbatha, T. P., and Modi, A. T. 2010. "Response of Local Mustard Germplasm to Water Stress." *S. Afri. J. Plant & Soil* 27: 328-30.

[23] Mabhaudhi, T. 2012. "Drought Tolerance and Water-Use of Selected South African Landraces of Taro (*Colocasia esculenta* L. Schott) and Bambara Groundnut (*Vigna subterranea* L. Verdc.)." Ph.D. thesis, University of KwaZulu-Natal.

[24] Anuradha, R., Balamurugan, P., Srimathi, P., and Sumathi, S. 2009. "Influence of Seed Coat Colour Variations on Seed Quality in Bengalgram cv CO 4 (*Cicer arietinum* L.)." *Legume Res*. 32: 136-8.

[25] Govindaraj, M., Masilamani, P., Alex Albert, V., and Bhaskaran, M. 2017. "Role of Antioxidant in Seed Quality—A Review." *Agric. Rev*. 38 (3): 180-90.

[26] McCauley, A., Jones, C., and Jacobsen, J. 2011. "Plant Nutrient Functions and Deficiency and Toxicity Symptoms." Nutrient Management Module No. 9, a self-study course from the MSU Extension Service Continuing Education Series, Montana State University Extension, 1-16. Accessed March 2, 2019. http://landresources.montana.edu/nm/documents/NM9.pdf.

[27] Lamont, B. B., and Groom, P. K. 2013. "Seeds as a Source of Carbon, Nitrogen, and Phosphorus for Seedling Establishment in Temperate Regions: A Synthesis." *Am. J. Plant Sci*. 4: 30-40.

[28] Toorop, P. E., Campos, C. R., Begg, G. S., Locardi, B., Squire, G. R., and Iannetta P. P. M. 2012. "Co-adaptation of Seed Dormancy and Flowering Time in the Arable Weed Capsella Bursa-Pastoris (Shepherd's Purse)." *Ann Bot*. 109: 481-9.

[29] Bloom, A. J. 2015. "The Increasing Importance of Distinguishing among Plant Nitrogen Sources." *Curr. Opin. Plant Biol*. 25: 10-6.

[30] Hemerly, A. 2016. "Genetic Controls of Biomass

Increase in Sugarcane by Association with Beneficial Nitrogen-Fixing Bacteria." In *Plant and Animal Genome XXIV Conference, Plant and Animal Genome*.

[31] Ding, Y. C., Chang, C. R., Luo, W., Wu, Y. S., Ren, X. L., Wang, P., and Xu, G. H. 2008. "High Potassium Aggravates the Oxidative Stress Induced by Magnesium Deficiency in Rice Leaves." *Pedosphere* 18 (3): 316-27.

[32] Hermans, C., Vuylsteke, M., Coppens, F., Cristescu, S. M., Harren, F. J., Inzé, D., and Verbruggen, N. 2010. "Systems Analysis of the Responses to Long-Term Magnesium Deficiency and Restoration in Arabidopsis Thaliana." *New Phytol*. 187 (1): 132-44.

[33] Khaleghi, E., Arzani, K., Moallemi, N., and Barzegar, M. 2012. "Evaluation of Chlorophyll Content and Chlorophyll Fluorescence Parameters and Relationships between Chlorophyll A, B and Chlorophyll Content Index under Water Stress in *Olea europaea* cv Dezful." *World Acad. Sci. Eng. Technol*. 68: 1154-7.

[34] Yang, H. S., Dobermann, A., Lindquist, J. L., Walters, D. T., Arkebauer, T. J., and Cassman, K. G. 2004. "Hybrid-Maize—A Maize Simulation Model That Combines Two Crop Modelling Approaches." *Field Crops Res*. 87: 131-54.

[35] Dalal, V. K., and Tripathy, B. C. 2012. "Modulation of Chlorophyll Biosynthesis by Water Stress in Rice Seedlings during Chloroplast Biogenesis." *Plant Cell Environ*. 35: 1685-703.

[36] Nursuaidah, H., Motior, M. R., Nazia, A. M., and Islam, M. A. 2014. "Growth and Photosynthetic Responses of Long Bean (*Vigna unguiculata*) and Mung Bean (*Vigna radiata*) Response to Fertilization." *J Anim Plant Sci*. 24 (2): 573-8.

[37] Terry, N., and Abadía, J. 1986. "Function of Iron in Chloroplasts." *J. Plant Nutrit*. 9: 609-46.

[38] Jamal, A., Moon, Y. S., and Abdin, M. Z. 2010. "Sulphur—A General Overview and Interaction with Nitrogen." *Aust J Crop Sci*. 4 (7): 523-9.

[39] Zlatev, Z., and Lidon, F. C. 2012. "An Overview on Drought Induced Changes in Plant Growth, Water Relations and Photosynthesis." *Emirates J Food Agri.* 24 (1): 57-72.

[40] Subbarao, G. V., Ito, O., Berry, W. L., and Wheeler, R. M. 2003. "Sodium—A Functional Plant Nutrient." *Crit Rev Plant Sci.* 22 (5): 391-416.

[41] de Vargas, R. L., Schuch, L. O. B., Barros, W. S., Rigo, G. A., Szareski, V. J., Carvalho, I. R., Pimentel, J. R., Troyjack, C., Jaques, L. B. A., de Souza, V. Q., da Rosa, T. C., Aumonde, T. Z., and Pedó, T. 2018. "Macronutrients and Micronutrients Variability in Soybean Seeds." *J. Agric. Sci*. 10 (4): 209-22.

[42] Tripathi, D. K., Singh, V. P., Chauhan, D. K., Prasad, S. M., and Dubey, N. K. 2014. "Role of Macronutrients in Plant Growth and Acclimation: Recent Advances and Future Prospective." In *Improvement of Crops in the Era of Climatic Changes*, edited by Ahmad, P., Wani, M., Azooz, M., and Phan Tran, L. S. New York: Springer, 197-216.

[43] Bai, Y., Wu, J., Clark, C. M., Naeem, S., Pan, Q., Huang, J., Hang, L., and Han, X. 2010. "Tradeoffs and Thresholds in the Effects of Nitrogen Addition on Biodiversity and Ecosystem Functioning: Evidence from Inner Mongolia Grasslands." *Glob. Change Biol*. 16: 358-72.

[44] Vance, C. P., Uhde-Stone, C., and Allan, D. L. 2003. "Phosphorus Acquisition and Use: Critical Adaptations by Plants for Securing a Nonrenewable Resource." *New Phytol*. 157: 423-47.

[45] Ferrari, M., Pelegrin, A. J., Souza, V. Q., Nardino, M., and Carvalho, I. R. 2014. "Effections on Yield Components of Different Treatment of Seeds and Leaf in the Soybean." *Biosphere Enciclopedia* 10: 532-8. (in Portuguese)

[46] Hirschi, K. D. 2004. "The Calcium Conundrum. Both Versatile Nutrient and Specific Signal." *Plant Physiol*. 136: 2438-42.

[47] Hepler, P. K. 2005. "Calcium: A Central Regulator of Plant Growth and Development." *Plant Cell* 17 (8): 2142-55.

[48] Murchie, E. H., and Lawson, T. 2013. "Chlorophyll Fluorescence Analysis: A Guide to Good Practice and Understanding Some New Applications." *J. Exp. Bot*. 64 (13): 3983-98.

[49] Maxwell, K., and Johnson, G. N. 2000. "Chlorophyll Fluorescence—A Practical Guide." *J. Exp. Bot*. 51 (354): 659-68.

[50] Bjorkman, O., and Demmig, B. 1987. "Photon Yield of O_2 Evolution and Chlorophyll Fluorescence Characteristics at 77 K among Vascular Plants of Diverse Origins." *Planta* 170: 489-504.

[51] Ow, L. F., Yeo, T. Y., and Sim, E. K. 2011. "Identification of Drought Tolerant Plants for Roadside Greening—An Evaluation of Chlorophyll Fluorescence as an Indicator to Screen for Drought Tolerance." *Urban for Urban Green* 10: 177-84.

[52] Johnson, G. N., Young, A. J., Scholes, J. D., and Horton, P. 1993. "The Dissipation of Excess Excitation Energy in British Plant Species." *Plant Cell Environ*. 16: 673-9.

[53] Havlin, J. L., Beaton, J. D., Nelson, W. L., and Tisdale, S. L. 2005. *Soil Fertility and Fertilizers: An Introduction to Nutrient Management*. Upper Saddle River, NJ: Pearson Prentice Hall.

[54] Butler, W. L. 1978. "Energy Distribution in the Photochemical Apparatus of Photosynthesis." *Annu. Rev. Plant Phys*. 29: 345-78.