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ASSESSMENT OF AGRONOMIC AND YIELD-RELATED TRAITS OF PYT GENOTYPES OF SOYBEAN

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DECLARATION

I NAKABUGO TENDO SIDNEY, declare that I am the sole writer and owner of this report. It has never been presented in any institution for the equivalent award.

Signature..#HAH.............. Date..04/09/2024.......

NAKABUGO TENDO SIDNEY

APPROVAL

This is to confirm that this special project research titled "Assessment of Agronomic and Yield-Related Traits of PYT Genotypes of Soybean", has been drafted and compiled under my supervision and is thus submitted for assessment with my explicit approval.

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AYT- Advanced Yield Trial

MAAIF- Ministry of Agriculture, Animal Industries and Fisheries

MAKCSID- Makerere Centre for Soybean Improvement and Development

PYT- Preliminary Yield Trial

ABSTRACT

Soybean (*Glycine max* L. merr) is an important leguminous crop for food and feed security globally and in Uganda. The Makerere University Centre for Soybean Improvement and Development (MAKCSID) develops soybean varieties with main objectives which include that the varieties developed are high-yielding with medium maturity of less than 120 days and also resistant to diseases with a focus on soybean rust. This study was conducted to assess the agronomic and yield-related traits of the sixteen genotypes at the Preliminary Yield Trial stage of the breeding programme. Randomized Complete Block Design with three replicates was used as the experimental layout at Makerere University Agricultural Research Institute, Kabanyolo. Analysis of variance was done to determine which traits varied significantly among the genotypes and correlation and path coefficient analysis were conducted to provide an understanding of the relationships between the traits and most especially to determine the effect of the traits on seed yield. The study found significant differences among the PYT genotypes for the traits days to 50% flowering, days from flowering to maturity, days to maturity, internode length, hundred-seed weight, resistance to soybean rust and seed yield. The seed yield was positively correlated to hundred-seed weight, pods per plant, seeds per pod, internode length, average plant height, and nodes per plant. Rust score was negatively correlated with seed yield. The key determinants of seed yield were number of pods per plant, hundred-seed weight, and resistance to soybean rust therefore these traits should be the focus of the breeding programme.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Biology, Origin, and Distribution of Soybean

The cultivated soybean, *Glycine max* L. merr, is an annual leguminous (Fabaceae) plant (Hymowitz and Newell, 1981). It has an erect growth habit and broad leaves. The plant bears self-fertilising flowers that may be white or purple. Upon fertilization, pods are produced and they contain seeds that may be yellowish, brown, or tan (Miladinovic et al., 2011). According to Vavilov, later modified by Zhuvosky, soybean comes from the Chinese-Japanese center of origin. The eastern half of North China is considered the primary center of diversity since this was where soybean was domesticated following a process of trial and error during the 11^{th} century (Hymowitz, 1970). The secondary gene centers comprise regions in southeast and south-central Asia where the introduction and diversity resulted from the establishment of sea and land routes and migration (Hymowitz and Newell, 1981). Through movements of people, soybean seed reached the West starting from Europe, then the United States.

The earliest mentions of soybean cultivation in Africa are dated as far back as 1858 in Alexandria (present-day Egypt) of which the seeds were likely sent from the Society for Acclimatization in France (Shurtleff and Aoyagi, 2009). Within East Africa, soybean cultivation is anecdotally reported to have started in Tanzania in 1907, introduced by the colonialists who were testing the ability of the crop to produce good yields in their colonies (Wilson, 2015).

The very first cultivation of soybean in Uganda was in 1913 resulting from the introduction of fifty-three cultivars from the United States, South Africa, Nigeria, and Trinidad (Leakey and Rubaihayo, 1970; Rubaihayo, 1969). It is attributed to the colonial era particularly the world wars to combat malnutrition among the soldiers (Bashaasha, 1992). In the late 1930s, variety trials started at Bukalasa and Serere and by 1940, some promising varieties were distributed (Rubaihayo, 1966). The initial boom of soybean production was sabotaged by the collapse of the market post World War 2, few varieties, and competing crops like coffee and cotton. However, production later increased due to efforts by MAAIF and the Faculty of Agriculture of Makerere University (Leakey and Rubaihayo, 1970; Tukamuhabwa et al., 2019).

1.2 Importance of Soybean

Soybean has many uses ranging from human and animal consumption to industrial uses and ecosystem functions. Soybean contains 40% protein on a dry matter basis which not only makes it the largest source of plant-based protein but also the cheapest on a protein per kilogram basis (Hymowitz and Newell, 1981; Miladinovic et al., 2011).

The grain can be eaten following a wide range of preparation methods (Singh et al., 2008). The whole grain may be roasted or allowed to sprout and then eaten. It can be fermented into soy paste, soy sauce, soy curd, and soy cheese. Soybean can also be processed into flour, meat alternatives, and soy milk. Uganda in particular consumes soybeans mainly through flour products which are turned into various composite porridges (Tukamuhabwa et al., 2019). Soybean meal is the major source of protein fed to animals in intensive production systems. This is crucial to produce pork, beef, poultry, milk, butter, and eggs (Hymowitz and Newell, 1981). Since it contains about 20% oil, another major product is crude soybean oil. The refined fraction of the oil is used to produce margarine, shortening, mayonnaise, salad dressings, and spreads. The other lecithin fraction is utilized as an emulsifying surface active, anti-spattering, and stabilizing agent. Some of the oil serves as an ingredient in industries manufacturing paint, ink, varnish, soap, linoleum, rubber, and cosmetics (Singh et al., 2008).

Soybean also plays some ecosystem functions such as soil improvement through its roots' symbiotic relationship with beneficial nitrogen-fixing microorganisms. When intercropped with cereals such as maize, the land and water use efficiency, the yield of the maize, and the total seed yield increase, with a land equivalent ratio greater than 1 (Kamara et al., 2020; Raza et al., 2022). Berdjour et al. (2020) found that the maize-soybean intercrop reduces weed biomass and diversity. It is recommended as part of crop rotation programs in which it aids soil improvement/ fertility (Sohidul et al., 2022). Soybean plants also break the lifecycle and continuity of the devastating witchweed, *Striga hermonitheca* (Kamara et al., 2020; Odhiambo et al., 2011). Soybean plant has morphological properties such as broad leaves and relatively short growth which shelter the soil surface, therefore, conserving soil moisture and reducing splash erosion (Tukamuhabwa et al., 2019).

Soybean production

Soybean is one of the most important oil crops in the world, only second to oil palm with production volumes of 388.098 million metric tonnes (FAOSTAT, 2023).The top five producers of soybean globally are Brazil producing 120 million metric tonnes making it the top producer, followed by the United States (116.37 million metric tonnes), Argentina (43.9 million metric tonnes), China mainland (20.28 million metric tonnes), and India (13 million metric tonnes) (FAOSTAT, 2023).

According to FAOSTAT (2023), South Africa, Nigeria, Zambia, Benin, and Togo are Africa's top five largest producers. Uganda is ranked tenth in Africa with a total annual production of 140,000 metric tonnes (FAOSTAT, 2023). In Uganda, the Lango sub-region produces the most soybean, followed by the Acholi subregion. Bunyoro and North Buganda have the lowest annual production based on the Uganda Bureau of Statistics (UBOS Annual Agriculture Survey (AAS), 2022).

Uganda has had several varieties over the years. The earliest ones include S-35, Congo 72, Clark 63, Bukalasa 4, no. 7 and Kabanyolo 1 which were lost amidst the civil conflicts from 1975 to 1986 (Bashaasha, 1992). Later on, varieties Nam 1 and Nam 2 were developed as a result of breeding efforts by MAAIF and Makerere University. However, they were destroyed by the outbreak of soybean rust disease in 1996 (Tukamuhabwa et al., 2012). Thereafter, efforts to breed new superior varieties led to the release of Namsoy 4M and Maksoy 1N in 2004, Maksoy 2N in 2008, Maksoy 3N in 2010, Maksoy 4N and Maksoy 5N in 2013, and the latest variety Maksoy 6N was released in 2017 (Tukamuhabwa et al., 2019).

1.3 Production constraints

Soybean production is limited by various factors which can be categorized into environmental (biotic and abiotic) and technological factors (Ngoune and Shelton, 2020).

The biotic factors include diseases, pests, and weeds. The fungal soybean rust disease caused by *Phakopsora pachyrhizi* is the most damaging disease, first observed in Uganda in 1996 causing massive yield losses. Other fungal diseases include frog eye leaf spot, red leaf blotch, downy mildew, Cercospora leaf spot, anthracnose, charcoal rot, green stem, blight, purple stain, and rots. There are also bacterial diseases such as bacterial pustules, and viral diseases such as mosaic virus vectored by pests like aphids and leafhoppers (Hartman and Murithi, 2017; Sinclair, 1989; Tukamuhabwa and Obua, 2015). The major pests of soybean include the groundnut leaf miner *Aproaerema modicella*, the bean leaf beetle *Cerotoma trifurcate*, and brown marmorated stink bug

Halyomorpha halys which attack soybean in the field while bruchids attack the seed/grain while in storage (Tukamuhabwa et al., 2019). Weeds are also a major problem, competing for resources with the crop, reducing yield (Tukamuhabwa and Obua, 2015).

Abiotic stresses include drought which reduces reproductive capacity (Max et al., 1993), flooding, and deficiencies or imbalances of macro and micronutrients which affect the availability of resources necessary for growth and good yield. These conditions also exacerbate the occurrence of certain diseases (Hartman and Murithi, 2017).

Technological factors include poor agronomic practices and managerial decisions taken due to prevailing socio-economic conditions. Soybean production has large labour demands from row planting, timely weeding, harvesting, threshing, and drying. Anecdotal evidence suggests that this limits acreage and also the ability of smallholder farmers to produce in bulk. The manual threshing methods employed by farmers lead to large amounts of losses (Dupare et al., 2010). The farmers have limited access to good seed due to low capital, seed-sharing traditions, and counterfeit seeds (Tukamuhabwa et al., 2019). There is also still a need for dissemination of knowledge and practice of appropriate agronomic practices.

1.4 Statement of the Problem

The Makerere University Centre for Soybean Improvement and Development (MAKCSID) has the main objective of producing soybean varieties that are high yielding with medium maturity of less than 120 days and also resistant to diseases with a focus on soybean rust (Tukamuhabwa et al., 2019). MAKCSID developed several improved soybean lines that were at the Preliminary Yield Trial (PYT) stage and needed to be advanced to the next stage of breeding. The basis of selection is variation among genotypes followed by advancement of those possessing traits that align with the objectives, particularly high yield.

However, no comprehensive study has been done to assess the agronomic and yield-related traits of the soybean lines at the Preliminary Yield Trial stage so their suitability for advancement was unknown. Additionally, current literature had conflicting information about which traits contributed directly or indirectly to seed yield which made it unclear which traits should be the focus of breeding. Therefore, this study was conducted to assess these traits to determine that there was variation and provide the basis for the selection of those genotypes with traits that contributed significantly to seed yield.

1.5 Objectives

1.5.1 General objective

To contribute to the development of soybean varieties that are high-yielding and widely adapted to the environments of Uganda.

1.6.2 Specific Objectives

- To determine the agronomic and yield-related characteristics of the PYT genotypes.
- To determine the relationship between seed yield and the agronomic and yield-related traits of the PYT genotypes.

1.6 Hypotheses

1. There is no significant difference in the agronomic and yield-related traits among the PYT genotypes.
2. There is no relationship between seed yield and agronomic and yield-related traits.

1.7 Justification

Breeding programs are very resource-intensive in terms of both time and funding. It is therefore of essence that the PYT genotypes being selected for advancement possess significantly superior agronomic and yield-related traits compared to the current existing varieties to justify the cost of the breeding program.

This research will provide the evidence required by other researchers to select only the superior genotypes to further advance as potential varieties. It will also ensure that soybean farmers in Uganda get the best variety released to ensure higher yields and profits.

In the long term, the findings of this research will contribute to higher agricultural productivity in Uganda which will mitigate food and feed insecurity hence contributing towards the sustainable development goal number two, Zero Hunger.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Agronomic Traits

Agronomic traits are those characteristics of a crop that impact its yield, quality, and ability to resist biotic and abiotic stresses. They include crop growth rate, plant height, number of nodes on the main stem, days to 50% flowering, days from flowering to maturity, days to physiological maturity, leaf area duration, number of branches, resistance to lodging, resistance to soybean rust disease, and effective filling period (Li et al., 2020; Qin et al., 2017; Vogel et al., 2021; Wang et al., 2016). The agronomic traits have high heritability values (59.8~95.1%) which shows that if they were selected for by strict criteria in the early stages of breeding, the probability of obtaining offspring with excellent target traits is high (Li et al., 2020; Song, 1999).

2.1.1 Days to 50% Flowering

Days to 50% flowering refers to the number of days from the date of planting to when 50% of the plants have at least one open flower (Parwada et al., 2020; Quartey et al., 2014). The relevance of this trait lies in the fact that the longer the days to 50% flowering, the longer the vegetative phase of the plant and therefore more days to maturity which leads to taller plants with more nodes, branches, and pods and possibly increased yield (Wang et al., 2016).

Even though soybean is generally placed under "short-day" plants meaning that floral initiation commences when nights are longer, the days to 50% flowering, often referred to as D50F, vary with the variety (Holshouser, 2010). Tsindi et al. (2019) conducted a multi-locational study in Uganda and reported that the days to 50% flowering for vegetable soybean genotypes ranged from 36 to 45 days. These findings are comparable to the range of 33.8 to 53 days in the Democratic Republic of Congo (Nkongolo and Kalonji-Mbuyi, 2011).

2.1.2 Days from flowering to maturity

The duration from flowering to maturity, commonly referred to as the reproductive period, is a critical phase in soybean development. Understanding this phase is essential for optimizing yield and developing soybean varieties that are suitable for specific growing conditions. Research by Hartwig and Kilen (1991) showed that the maturity group classification system is an effective method for categorizing soybean varieties based on when they flower and mature and that varieties in earlier maturity groups generally have shorter reproductive periods compared to those in later groups.

The period from flowering to maturity in soybeans varies depending on genetic factors, environmental conditions, and geographic locations. Genetic variation significantly influences the reproductive period in soybean whereby different soybean cultivars exhibit a wide range of flowering to maturity durations. Various genes, such as E1, E2, E3, E4, and Dt1, play crucial roles in regulating flowering and maturity in soybeans, with different alleles either delaying or accelerating these processes (Ort et al., 2022). Environmental factors, particularly temperature and photoperiod, play a crucial role in determining the length of the period from flowering to maturity in soybeans. Major et al. (1975) demonstrated that longer days promote earlier flowering, thereby affecting the subsequent period to maturity. Temperature also significantly impacts the rate of development during the reproductive phase whereby high temperatures can accelerate the reproductive process, shortening the duration from flowering to maturity (Gogoi et al., 2018). On the other hand, cooler temperatures can prolong this period, potentially affecting yield outcomes. Agronomic practices, including planting date, row spacing, and irrigation, also influence the days from flowering to maturity in soybean. Planting date is a critical factor whereby early planting typically leads to a longer vegetative period and a subsequently shorter reproductive period. Egli (1994) found that delayed planting results in a shorter vegetative period but can extend the reproductive phase, impacting overall growth and yield. Row spacing and plant density can affect light interception and canopy development, influencing the duration from flowering to maturity. Moreover, irrigation practices during the reproductive phase can mitigate the stress effects of drought, potentially altering the length of this period (Heatherly, 1993).

Studies have shown that the flowering-to-maturity period in soybeans can range from 50 to 85 days (Vlasova et al., 2023), or as widely as 12 to 56 days (Liu et al., 2021). Sinegovskaya and Levina, (2021) found that the length of the reproductive period in soybeans varied depending on the daylight duration, with a maximum of 96 days for plants sown on May 28 and a minimum of 89 days for plants sown on June 3.

2.1.3 Days to Physiological Maturity

Soybean plants undergo two major stages, the vegetative growth stage and the reproductive growth stage, which is further broken down into sequential phases, VE to V3 and R1 to R8, from planting to harvest. Among these phases, the R7 is considered the one at which a soybean plant has attained physiological maturity at which there is no additional accumulation of dry weight, and one normal pod has attained mature colour (Tukamuhabwa and Obua, 2015). However, harvest is usually done at the R8 stage when the leaves have dropped and over 95% of the pods are dry (Rubaihayo, 1969).

Days to maturity have profound implications for agronomic practices and yield. Genotypes with shorter DTM can be advantageous in regions prone to drought allowing farmers to harvest the crop before the onset of dry weather conditions. On the other hand, genotypes with longer DTM may be preferred in regions with longer growing seasons, because they have the potential for higher biomass accumulation and seed yield (Ortel et al., 2020). However, more days to maturity may not always be advantageous as shown by a study conducted in Uganda which indicated that at R6, late-maturing lines have higher rust severities compared to early and medium-maturing lines, which may negatively influence seed yield (Kawuki et al., 2004).

Studies have shown considerable variability in days to physiological maturity among soybean genotypes, which can be attributed to genetic differences and environmental factors such as abiotic and biotic stresses like drought and insect feeding that cause flower and pod abortion, delaying maturity (Holshouser, 2010). In a study by Alliprandini et al. (2009), the number of days to maturity among various soybean genotypes in Brazil varied significantly; the lowest was 108 days and the highest was 147 days. Another study in Canada found that soybean genotypes reached 95% maturity in 114-132 days (Thai et al., 2019). Ravelombola et al. (2021) reported a range of 77.3 to 139 days for a study on 250 accessions. According to Tukamuhabwa and Obua (2015), most Ugandan varieties of soybean take between 90 to 120 days to mature. This illustrates the genetic diversity within the crop and its potential for breeding programs aimed at specific maturity periods.

2.1.4 Average Plant Height

The plant height of soybean is the length from the point at which the shoot emerges from the ground to the tip of the stem, taken at the physiological maturity of the plant. Plant height is an indicator of plant health. There is a negative correlation between plant height and canopy temperature meaning that taller plants tend to have lower canopy temperatures (Fletcher and Fisher, 2019). Various studies have found relationships between plant height and yield in soybean. Taller plants have been found to yield more due to greater biomass and photosynthetic area (Board and Tan Qiang, 1995). Egli (2010) found that the higher the plant height, the higher the number of pods and higher seed weight hence higher yield. On the other hand, excessively tall plants are susceptible to lodging which has a negative impact on yield (Woods, 1977). In a study to determine if there is a correlation between plant height and yield, Diondra et al. (2008) found no relationship between the two because yield and plant height are complex polygenic traits inherited in a quantitative fashion.

A study in North Carolina reported soybean plants with height ranging from 31.2cm to 170cm with an average of 62.4cm (Diondra et al., 2008). Another study reported a minimum plant height of 35.9cm and a maximum of 101cm with an average of 70.1cm (Fletcher and Fisher, 2019). A study on 250 accessions reported a very low height of 18.5cm and the maximum for that same study was 162.9cm (Ravelombola et al., 2021). A study on the morpho-variability and agronomic characteristics of soybean accessions from the Democratic Republic of Congo gene pool found that all the accessions were less than 50cm tall with 75% shorter than 40cm (Mudibu et al., 2011). Among the Mak series of soybean varieties, the plant height ranges from 52cm to 90cm with Maksoy 1N as the shortest and Maksoy 2N and Maksoy 3N as the tallest (Tukamuhabwa et al., 2019). Mugisha (2016) reported their lowest height as 59.9cm in a determinate genotype and the highest was 90 cm in a semi-determinate genotype, finding a grand mean of 76.3cm for the 30 soybean genotypes at the Advanced Yield Trial stage.

2.1.5 Number of branches

The number of branches impacts soybean yield in such a way that more branches mean more pods and more seeds since pods grow at the nodes on the main stem and branches (Board, 1987). Branching in soybean is a polygenic trait influenced by several quantitative trait loci and also environmental factors such as light, temperature, and planting density (Li et al., 2020). Soybean plants have a compensatory capacity to produce a higher number of branches in response to the spatial arrangement of the crops. High planting density generally reduces branching due to competition for light and nutrients which affects axillary bud development while lower densities promote more branching. Initially increases in branch number increase yield, but beyond a certain point, yield plateaus and decreases due to competition for resources and the trade-off between branching and optimal planting density (Xu et al., 2021). However, Garcia et al. (2018) did not find a significant increase in branch number with a decrease in inter-row spacing. Li et al. (2020) found a maximum mean branch number of 9.8 per plant. Meanwhile, other studies found a range of 1 to 7.33 (Thio et al., 2022; Zhang et al., 2021).

2.1.6 Number of nodes

The number of nodes is a significant yield component determined in the vegetative growth phase and influenced by various factors like water availability, soil fertility, row spacing, plant density, light interception, and genotypes (Parvej et al., 2016; Vogel et al., 2021). According to Allen et al. (2018), soybean plants can have up to 15-16 nodes under normal field conditions, but exposure to higher temperatures can lead to increased node production due to prolonged vegetative growth. However, a fixed-observation study from 1998 to 2024 revealed that high temperature and drought stress actually reduced the number of nodes by 0.1 to 2.9 (Li et al., 2024). Dozet et al. (2008) reported a range of 12.05 to 13.51 nodes, with increased row spacing leading to higher numbers of fertile nodes. A study was carried out to assess the agronomic traits of 173 soybean genotypes in 3 different geographical areas in China and the mean number of nodes on the main stem was reported as 17.8, 17.5, and 17.1 nodes (Li et al., 2020). (Fahim et al., 2021) found that the number of nodes on the main stem of 821 accessions varied from 8.8 to 31.1, with an average of 16.3 nodes.

2.1.7 Internode Length

This is the length or distance between two nodes on the main stem, affected by genes and the environment. It directly influences plant height in that longer internodes imply taller plants.

Internode length is affected by the spectral distribution of light in the canopy in such a way that the decrease of photosynthetically active radiation (PAR) and the ratio of red/far-red light can lead to significant elongation of the internodes (Xu et al., 2021). Internode length was found to be the most drought-sensitive factor during the vegetative and flowering stages whereby the internode length of the Weber soybean variety was reduced in drought-stressed treatments (Desclaux et al., 2000). In another study, Oki et al. (2018) reported an average internode length of 3.7cm for the cultivar Fukuyutaka and 2.9cm for the cultivar Y2.

2.1.8 Pod Clearance

Pod clearance is the height of the lowest pod on the soybean plant, and it contributes to the extent of harvest losses and facilitation of mechanized harvesting. Greater pod clearance reduces harvest losses especially since the lowest pods usually have the most and largest seeds and also higher pod clearance reduces the risks of pods being cut by harvesters, thereby increasing overall yield (Thai et al., 2019). Genotypes with low pod clearance may expose soybean pods to soil splash when it rains and this increases the chances of mold (Thio et al., 2022). Qin et al. (2017) found some evidence supporting a relationship between the height of the lowest pod and yield but it is inconclusive as there are both positive and negative relationships.

Thio et al. (2022) analyzed pod clearance among 24 genotypes in Burkina Faso and found a range of 11cm to 29cm. However, Thai et al. (2019) found much lower values of 3cm to 8.6cm in Southern Alberta, Canada. In their study comparing harvest efficiency in conventional versus organic cropping systems in Germany, Beiküfner et al. (2019) found that pod clearance was consistently higher in conventional systems, with a maximum of 12.8 cm, than in organic systems which had maximum of 9.4cm. The minimum pod clearance was 7.9cm for conventional system and 5.6cm for the organic system.

2.1.9 Soybean rust disease resistance

First reported in Uganda in 1996, soybean rust caused by the fungus *Phakopsora pachyrhizi*, is the most devastating foliar disease affecting soybean production in Uganda (Hartman and Murithi, 2017; Levy, 2005). The symptoms of soybean rust include reddish-brown, tan, or mixed lesions on the leaves which later develop small pustules that break open and release uredospores (Miles et al., 2006). Reddish-brown lesions imply that the interaction between the particular soybean genotype and the rust fungus is incompatible and there is some resistance while the tan lesions indicate that the genotype is susceptible (Goellner et al., 2010). Iinfection causes premature plant defoliation (Kumudini et al., 2008) leading to yield losses which can range between 18% and 55%, but can be as high as 80%, as has been reported in Uganda and Zimbabwe (Levy, 2005; Oloka et al., 2008).

Temperature and moisture increase the prevalence of soybean rust with the optimum conditions for spore germination being temperatures of 17°C to 29 °C (Bonde et al., 2012), and relative humidity higher than 85% (Melching et al., 1989). Therefore, the climate conditions in Uganda favor the infection of soybean by *P. pachyrhizi* throughout the year (Pivonia and Yang, 2004).

Tukamuhabwa et al. (2010) highlighted the importance of continuously broadening the genetic base of local soybean germplasm to maintain effective control of rust. It is crucial to select genotypes that show resistance or tolerance to the devastating soybean rust disease because most existing ones are susceptible to it (Murithi et al., 2021). The *P. pachyrhizi* fungus has several pathotypes that vary across locations in Uganda so it is important to continuously identify possible sources of resistance as suggested by (Obua, 2013) who found that the lowest mean score for rust severity was 3.1 and the highest was 4.0 using the scale of (Iqbal et al., 2004). Murithi et al. (2021) screened 71 genotypes for resistance to soybean rust disease in East Africa and of these, seven had reddish-brown lesions and showed low disease severities in all of the screening environments.

2.2 Yield-related traits of soybean lines

The yield of any crop is a product of the highest-level traits that are directly related to the output of that crop. These characteristics are known as yield components and have been used since the 1920s to analyse yield (Engledow and Wadham, 1923). For soybean, the yield components are the number of pods per plant, 100-seed weight, number of seeds per pod and seed weight (Li et al., 2020; Qin et al., 2017; Vogel et al., 2021).

2.2.1 Number of pods per plant

The pods are the fruit of the plant, containing the seeds and their number per plant is a function of genetics and environment. Within a given genotype, pod number is affected by environmental variations such as drought or water stress and light conditions (Liu et al., 2009; Liu et al., 2003; Liu et al., 2004).

Liu et al. (2009) found that the number of pods per plant was affected by light conditions whereby light enrichment imposed during the early flowering stage increased the availability of assimilates to the developing reproductive structures and decreased flower and pod abscission with a resultant increase in the final pod number at harvest. Other findings show that drought stress significantly reduced pod set by 40% and resulted in a 50% seed yield reduction (Liu et al., 2003). The plant population is another factor that affects the number of pods per plant. Garcia et al. (2018) studied the effect of spacing at four treatment levels 0.25, 0.50, 0.75, and 1.00m, and found that increasing spacing between rows reduces pods per plant with a confidence level greater than 95%.

Kayaga (2019 and Mugisha (2016) assessed this parameter in soybean genotypes in Uganda and found averages of 35.5 and 27.88 pods respectively. It is noteworthy that according to the findings of Kayaga (2019), the genotype with the least number of pods per plant had the highest number of seeds per pod which points to some compensatory effect.

2.2.2 Number of seeds per pod

Increased seed number means increased sink capacity. Seed number is strongly determined by the internal genetic mechanism however it can be modified by environmental conditions such as light enrichment which tends to increase seed number per pod compared with that of ambient light (Liu et al., 2009).

Another environmental condition that affects the number of seeds per pod is water availability whereby early water stress during seed filling was reported to reduce the number of seeds per pod (Desclaux et al., 2000). The same study also found that plants subjected to early reproductive drought stress had a higher number of seeds per pod than control plants (110% for low-intensity stress). Presumably, this was a compensation phenomenon associated with low pod numbers in these treatments.

Several studies have found the number of seeds per pod to be between 1 to 3. Księżak and Bojarszczuk (2022) found the lowest mean to be 1.4 and the highest was 2.1 seeds. Biswas et al. (2016) reported similar findings of 1.17 to 2.09 seeds per pod.

2.2.3 Hundred seed weight

This is the weight of 100 seeds of a given variety. It is an essential parameter for soybean yield and it is also an indicator of the inheritance of quantitative traits affected by genotype and environment (Qi et al., 2020). Environmental factors that affect the hundred seed weight include drought stress especially if it occurred during the early seed-filling period (Desclaux et al., 2000). Liu et al. (2004) reported that drought stress substantially decreased the quantity of non-structural carbohydrates accumulated in soybean pods leading to low seed weight. Hundred-seed weight has been found to vary significantly across regions. In China, Li et al. (2020) reported a mean hundred seed weight of 19.6g which is similar to the 19.97g reported by Mugisha (2016). In their study identifying QTNs controlling 100-seed weight, Qi et al. (2020) found maximum value of 22.55g among large-seeded lines and minimum value of 16.53 among small-seeded lines. The range for hundred-seed weight of soybean in the Sichuan and Chongqing eco-regions population was 4.82–33.35g, as per a genome-wide association study (He et al., 2021).

2.2.3 Seed yield

Yield is a complex quantitative trait controlled by many genes (Li et al., 2020). Although it is genetically controlled, the seed yield of soybeans is also a result of an interaction between a variety's genetic potential, the environment, and farming practices (Tukamuhabwa et al., 2012). Total yield can be defined as the product of seed number per unit of land area or 100-seed weight per unit of land area or plot (Mugisha, 2016; Vogel et al., 2021).

Assessment of yield for soybean has to be done on substantial field trials because the components that define soybean yield reflect that yield culminates from a population of plants growing together in a community and not an individual plant (Vogel et al., 2021).

In their experimental field trial, Nkongolo and Kalonji-Mbuyi (2011) in DR-Congo found the lowest-yielding genotype to give 650 kg/ha and the highest was 2898 kg/ha. This is in a similar range as the highest yield of 2996.5 kg/ha found by Xu et al. (2022) in China. In Uganda, Tukamuhabwa et al. (2012) conducted a study of the genotype by environment interaction of advanced soybean lines and found a single genotype to be the highest yielding across environments with an average of 1409 kg ha^{-1}. A few years later, Obua et al. (2020) conducted a similar study and found the highest mean yield of 1277 kg ha^{-1}. Another study reported 1207 kg ha^{-1} as the highest mean seed yield (Obua et al., 2021).

2.3 Relationship between seed yield and yield-related traits

Seed yield has significant positive correlations with the number of pods, seeds per pod, and 100-seed weight**.** Of these, the number of seeds per pod and 100-seed weight are the major ones that affect seed yield (Li et al., 2020; Qin et al., 2017; Wang et al., 2016). However, 100-seed weight was found to be negatively correlated with the number of seeds which implies that yield improvement requires improving the seed number without reducing the 100-seed weight (Qin et al., 2017).

For yield improvement to occur, there is also a need to strike a balance between all the agronomic and yield traits (Wang et al., 2016). Li et al. (2020) suggests to prioritise plants with more pods, seeds, and 100-seed weight and thereafter consider their plant height, number of nodes on the main stem, number of branches, and longer growth period.

In the pursuit of higher and stable yields, it is crucial to consider the significant effect of the genotype by environment interaction on agronomic traits and consequently yield. Li et al. (2020) found that the yield of some cultivars was significantly reduced when they were grown only 2^0N of their normal cultivation zones. Some of these confounding factors include planting density (Qin et al., 2017) soil type and conditions, pest, and disease management, and unpredictable factors in each environment such as precipitation, temperature, and humidity. Breeding for higher yield will require optimization of plant architecture and adaptation to the local environment.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Experimental Materials

The experimental materials used were the 16 genotypes developed by the Makerere University Centre for Soybean Improvement and Development which are at the Preliminary Yield Test stage including a local check, Maksoy 6N (Table 1). These are;

Table 1: Soybean Genotypes used in the current study

	Genotype Name	Comment
1.	PYT 6N	Local Check
2.	6N Selected	Local Check
3.	4M × 11.2-1	Advanced line
4.	4M × 14.1-24	Advanced line
5.	6N × Squire-C	Advanced line
6.	6N × 2N-2-3	Advanced line
7.	Plot 117 PYT 2020B	Advanced line
8.	G 7955 × 2N	Advanced line
9.	8.11 × 2N-2A	Advanced line
10.	SPS 6N × 2N-2	Advanced line
11.	2N × 5N-2	Advanced line
12.	Signal × 5N	Advanced line
13.	8.11 × 2N-4	Advanced line
14.	6N × Saga-P-3-1	Advanced line
15.	SPS BSPS 48A-28-1	Advanced line
16.	6N × 2N-2-4-2	Advanced line

3.2 Experimental Location

The research was conducted at the Makerere University Agricultural Research Institute, Kabanyolo (MUARIK) located in Busukuma sub-county in Wakiso district of Central Uganda. The site is at 0^{0}281N and 32^{0}271E, at an altitude of 1204m above sea level. Climate characteristics are moderate and well-distributed bi-modal rainfall, and average temperatures are between 20^{0}C-30^{0}C. The soil is deep and well-drained and the land is gently sloping.

3.3 Experimental design

The Randomised Complete Block Design (RCBD) with three replicates was employed. The plot size was 5 x 1.8 metres. Each plot treatment was a single genotype planted in 3 rows of 5 metres long. Intra-row spacing of 5cm and inter-row spacing of 60cm was used.

Thinning was done to ensure appropriate intra-row spacing. Weeding was done using hoes within the third and eighth weeks after planting to keep the plots weed-free. Scouting for soybean rust started in the fourth week and continued weekly throughout the rest of the experimental period.

3.4 Data Collection

The primary method of data collection was physical observation coupled with meticulous record-keeping. Data on some of the agronomic traits was collected in the early growth stage before physiological maturity for example days to 50% flowering was collected when observations were made that 50% of a given genotype had flowered.

Resistance to soybean rust disease was scored weekly. A scale of 1-5 adopted from Iqbal et al. (2004) and Miles et al. (2006) was used for the disease rating where;

1= no visible lesions (highly resistant)

2= few scattered lesions (resistant)

3= moderate number of lesions (moderately resistant)

4= abundant number of lesions (susceptible)

5= prolific lesions over most of the leaf (highly susceptible)

During the growth period and at the late stages of growth (R7-R8), the data in Table 2 on agronomic traits was collected from 10 random samples of each genotype using the corresponding method.

Table 2: Agronomic traits and the corresponding method of data collection

Agronomic trait	Method of data collection
Days to 50% Flowering	Observation and reviewing records of planting dates
Days from Flowering to Maturity	Observation and review of records
Days to physiological Maturity	Observation and reviewing records of planting dates
Average Plant height	Measurement using a meter ruler
Number of Branches	Observation and counting
Number of nodes	Observation and counting
Internode length	Measurement using ruler
Pod clearance	Measurement using a ruler
Resistance to soybean rust disease	Observation and scoring from 1 to 5

Upon physiological maturity, the following data (Table 3) on yield-related traits was collected from 10 random samples for each genotype using the corresponding method.

Table 3: Yield-related traits and the corresponding method of data collection

Yield-related trait	Method of data collection
Number of pods per plant	Observation and counting
Number of seeds per pod	Observation and counting
100-seed weight (100SW)	Weighing using a precision weighing scale Ohaus Traveler TA 3001 JP Compact Electronic Balance (3000g, 0.1g)
Seed yield*	Weighing using a weighing scale

*The seed yield was obtained by weighing threshed, air-dried soybeans and expressing the figure in grams per plot which was then converted to yield in kg ha^{-1}.

3.5 Data Analysis

The quantitative data underwent Analysis of variance (ANOVA) using the agricolae package in R software Version 4.3.3. Correlation and path coefficient analysis was conducted using packages lavaan, semplot, psych and Hmisc to analyse the relationship between the observed traits and seed yield. The causal model in the path coefficient analysis; the agronomic and yield-related traits were taken as the independent variables and seed yield as the dependent variable.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 RESULTS

4.1.1 Agronomic traits

Days to 50% Flowering

There were significant differences in the days to 50% flowering at $p < 0.001$ due to variation in genotypes (Appendix 1). Genotype 4M × 14.1-24 took the longest time of 51 days to reach 50% flowering while genotype Signal × 5N took the shortest time of 40.3 days. The mean days for 50% flowering were 44.6 days (Table 4).

Days from Flowering to Maturity

The genotypes varied significantly at $p < 0.01$ in the days from flowering to maturity (Appendix 2). The minimum number of days was 50 in genotype Plot 117 PYT 2020B while the maximum was 60.7 days in genotype Signal×5N. The mean number of days from flowering to maturity was 55.8 days (Table 4).

Days to Maturity

The genotypes showed significant differences in the days taken to attain physiological maturity at a significance level of $p < 0.001$ (Appendix 3). The mean number of days was 100.4 with genotype 4M × 14.1-24 taking the maximum days of 107 and genotype Plot 117 PYT 2020B taking the minimum of 93.7 days to attain physiological maturity (Table 4).

Average Plant Height

Differences in plant height were significant at $p < 0.05$ among the genotypes assessed (Appendix 4). The tallest genotypes were 2N × 5N-2 and 8.11 × 2N-4 at 95.1cm and 93.7cm respectively. The shortest genotype was SPS BSPS 48A-28-1 at 63.5 cm and the mean plant height was 81.4 cm (Table 4).

Branches

Genotypic differences in the number of branches were highly significant at $p < 0.01$ (Appendix 5). Genotype 8.11 × 2N-2A had an average of 3.2 branches which was the highest. There were five genotypes with average branch numbers below 1 and these were 6N Selected (0.9), Signal × 5N (0.9), PYT 6N (0.7), Plot 117 PYT 2020B (0.4), and BSPS 48A-28-1 which had the lowest average branch number of 0.3. The grand mean for all the genotypes was 1.7 branches (Table 4).

Internode length

Internode length had significant differences at $p < 0.05$ among genotypes (Appendix 6), with a mean of 7.0cm. The maximum internode length was 8.3cm, observed on genotype 6N × Saga-P-3-1 while the minimum was 5.8cm, observed on genotype SPS BSPS 48A-28-1 (Table 4).

Resistance to soybean rust disease

There was a highly significant difference in resistance to soybean rust at $p < 0.001$ arising from genotypic differences (Appendix 7). The genotype that was observed to be the most resistant had the lowest soybean rust score of 1.7 and this was genotype 6N × Saga-P-3-1. Among the assessed genotypes, the genotypes with the least resistance had a score of 4 each and these were 6N × 2N-2-4-2, G 7955 × 2N and 6N × 2N-2-3 (Table 4).

Table 4: Means of agronomic traits for all genotypes

Genotype	D50F	DFM	DTM	Avg.PH	Branches	Internode length	Rust	Nodes	Pod clearance
6N × Saga-P-3-1	43.3	53.0	96.3	75.8	1.5	8.3	1.7	12.7	11.1
2N × 5N-2	45.0	59.0	104.0	95.1	1.7	6.5	3.0	16.5	8.1
8.11 × 2N-4	41.3	58.3	99.7	93.7	2.1	6.6	3.7	16.4	11.8
Plot 117 PYT 2020B	43.7	50.0	93.7	77.9	0.4	5.9	3.3	13.9	10.5
6N × Squire-C	41.7	53.7	95.3	73.7	2.9	7.7	3.0	13.7	9.7
6N × 2N-2-3	46.0	52.7	98.7	86.1	2.8	7.0	4.0	15.5	10.6
6N Selected	45.7	53.0	98.7	72.7	0.9	7.0	2.7	11.7	8.3
PYT 6N	46.0	54.0	100.0	70.8	0.7	7.4	3.0	11.6	10.8
Signal × 5N	40.3	60.7	101.0	85.1	0.9	6.5	3.7	13.9	10.6
SPS 6N × 2N-2	44.3	58.7	103.0	90.9	2.8	7.9	3.7	14.7	8.9
8.11 × 2N-2A	47.3	59.0	106.3	87.0	3.2	7.1	3.0	13.7	9.2
6N × 2N-2-4-2	43.3	56.0	99.3	91.6	2.3	7.9	4.0	16.0	9.4
G 7955 × 2N	44.0	55.3	99.3	73.6	1.9	6.1	4.0	15.1	9.3
4M × 11.2-1	48.7	58.0	106.7	85.5	2.0	6.4	2.7	15.1	8.5
SPS BSPS 48A-28-1	41.3	55.7	97.0	63.5	0.3	5.8	3.0	11.8	10.5
4M × 14.1-24	51.0	56.0	107.0	79.7	1.1	7.3	3.3	14.2	9.6
Mean	44.6	55.8	100.4	81.4	1.7	7.0	3.2	14.2	9.8
CV (%)	2.3	4.8	2.5	12.8	53.4	11.8	12.7	15.1	21.3
LSD	1.7	4.4	4.2	17.3	1.5	1.4	0.7	3.6	3.5
Min	40.3	50.0	93.7	63.5	0.3	5.8	1.7	11.6	8.1
Max	51.0	60.7	107.0	95.1	3.2	8.3	4.0	16.5	11.8

4.1.2 Seed Yield and Yield-related traits

Number of seeds per pod

The analysis showed that at $p < 0.05$, there were significant differences in the number of seeds per pod, among the genotypes (Appendix 11). Genotype 6N × Saga-P-3-1 had the highest number at 3 seeds while five genotypes each had the minimum of 2 seeds per pod. These were 6N × Squire-C, 6N × 2N-2-3, 8.11 × 2N-2A ,6N × 2N-2-4-2, and G 7955 × 2N (Table 5). The mean number of seeds per pod was 2.4 (Table 5).

Hundred-seed weight (100SW)

The genotypic differences in the hundred-seed weight were highly significant at $p < 0.001$ (Appendix 12) with a mean of 14.2g (Table 5). Genotype 6N×Saga-P-3-1 had the highest hundred-seed weight of 19.9g while genotype Signal×5N had the lowest of 10.3g (Table 5).

Seed yield in kg ha^{-1}

The genotypes had a significant difference in yield at $p < 0.01$ (Appendix 13). The highest-yielding genotype was 6N×Saga-P-3-1 with 2059.3 kg ha^{-1}, followed by 2N×5N-2 (1460.4 kg ha^{-1}) and 8.11×2N-4 (1417.0 kg ha^{-1}). The lowest yield was observed in genotypes 4M×11.2-1 (829.6 kg ha^{-1}), SPS BSPS 48A-28-1 (748.9 kg ha^{-1}) and the very least was 4M×14.1-24 (655.2 kg ha^{-1}) (Table 5). Mean seed yield was 1178 kg ha^{-1} (Table 5).

Table 5: Means of seed yield and yield-related traits for all genotypes

Genotype	Pods plant^{-1}	Seeds pod^{-1}	100SW	Yield (kg ha^{-1})
6N × Saga-P-3-1	27.7	3.0	19.9	2059.3
2N × 5N-2	44.8	2.7	15.1	1460.4
8.11 × 2N-4	37.9	2.3	13.5	1417.0
Plot 117 PYT 2020B	26.9	3.0	12.6	1380.0
6N × Squire-C	33.2	2.0	16.3	1372.2
6N × 2N-2-3	49.1	2.0	14.2	1324.4
6N Selected	23.9	2.3	14.3	1289.3
PYT 6N	25.9	2.7	14.4	1248.5
Signal × 5N	29.6	2.7	10.3	1132.6
SPS 6N × 2N-2	34.1	2.3	13.8	1027.0
8.11 × 2N-2A	29.6	2.0	15.0	1011.8
6N × 2N-2-4-2	33.0	2.0	13.6	959.2
G 7955 × 2N	36.8	2.0	12.7	932.6
4M × 11.2-1	26.1	2.7	14.9	829.6
SPS BSPS 48A-28-1	21.1	2.3	12.7	748.9
4M × 14.1-24	22.9	2.3	13.4	655.2
Mean	31.4	2.4	14.2	1178.0
CV (%)	34.9	16.8	3.3	26.9
LSD	18.3	0.7	0.8	527.8
Min	21.1	2.0	10.3	655.2
Max	49.1	3.0	19.9	2059.3

4.1.3 Correlation analysis between observed traits and seed yield

Figure 1 shows the nature and strength of correlation between the different traits examined in this study. The traits were positively correlated to some of the other traits, and negatively correlated to others, as indicated by the shading (green is for positive as red is for negative correlation). The strength of the correlation is denoted by the intensity of the color saturation and the magnitude of the correlation coefficient.

Days from flowering to maturity were omitted from the correlation and path coefficient analysis because it was derived from days to 50% flowering and days to maturity therefore it led to multicollinearity within the model which skewed the results and altered the Akaike value.

Positive correlations

Hundred-seed weight (0.56) and number of pods per plant (0.5) had highly significant correlations with seed yield at $p < 0.001$ while internode length (0.36), average plant height (0.36) number of nodes (0.33) and seeds per pod (0.33) were significant at $p < 0.05$.

Average plant height was positively correlated with the internode length (0.36), number of nodes (0.8), days to maturity (0.51), pods per plant (0.68), and branches (0.49). Hundred-seed weight was positively correlated with internode length (0.49). Internode length was positively correlated with hundred-seed weight (0.49) and number of branches (0.34). Pods per plant were positively correlated with number of nodes (0.81), average plant height (0.68) and branches (0.67). Number of nodes was positively correlated with pods per plant (0.81), branches (0.55), and days to maturity (0.44) and average plant height.

Number of branches showed positive correlations at $p < 0.05$ with days to physiological maturity (0.33). Positive correlations at $p < 0.001$ were obtained between; days to physiological maturity and days to 50% flowering (0.59).

Negative Correlations

The soybean rust score was negatively correlated (-0.41) with seed yield at $p < 0.01$ meaning that a high rust score was associated with a low seed yield. A significant negative correlation at $p < 0.001$ was got between soybean rust score and hundred-seed weight (-0.66) meaning that when the genotype had a high rust score, the hundred-seed weight was low. There was also a negative correlation between soybean rust score and number of seeds per pod (-0.33) at $p < 0.05$ significance level.

Traits that had a correlation coefficient of 0 or close to 0 had almost no relationship between them for example there was no correlation between number of seeds per pod and internode length.

	Yield	Avg.PH	P.C	I.L	Nodes	SPP	D50F	DTM	PPP	100SW	Rust	BRC
Yield	1											
Avg.PH	0.36*	1										
P.C	-0.02	-0.17	1									
I.L	0.36*	0.36*	0.13	1								
Nodes	0.33*	0.8***	-0.21	0.17	1							
SPP	0.33*	0.13	-0.17	0.00	0.1	1						
D50F	-0.26	0.10	-0.08	0.16	0.03	-0.02	1					
DTM	-0.17	0.51***	-0.24	0.09	0.44**	-0.04	0.59***	1				
PPP	0.5***	0.68***	-0.16	0.21	0.81***	-0.02	-0.01	0.26	1			
100SW	0.56***	0.04	-0.06	0.49***	-0.01	0.17	0.15	-0.03	0.1	1		
Rust	-0.41**	0.18	0.17	-0.15	0.25	-0.33*	-0.06	-0.02	0.2	-0.66***	1	
BRC	0.19	0.49***	-0.21	0.34*	0.55***	-0.23	0.16	0.33*	0.67***	0.26	0.15	1

***, ** and *** indicate significance at α ≤ 0.05, α ≤ 0.01, and α ≤ 0.001 respectively**

Avg.PH- Average Plant Height, BRC-Branches, D50F- Days to 50% Flowering, DTM- Days to Maturity, I.L- Internode Len P.C-Pod Clearance, PPP-Pods Per Plant, SPP-Seeds per pod

Figure 1: Correlation matrix for the agronomic and yield-related traits

4.1.4 Path Coefficient Analysis

Table 6 shows the causal relationship of the agronomic and yield-related traits on seed yield. The traits that had significant positive effect on seed yield were hundred-seed weight, number of pods per plant and the average plant height in order of impact. Both soybean rust and number of branches had a negative effect on seed yield at $p < 0.05$ significance level. However, the rust score had a more negative effect (-177.149) than the number of branches (-87.426). Summarily, from the regression analysis, the hundred-seed weight, pods per plant and average plant height were the traits that positively and significantly contributed to seed yield while high rust scores and many branches decreased yield.

Table 6: Regression analysis between seed yield and observed traits

	Estimate	Std.Err	z-value	P(>|z|)	Std.lv	Std.all
Yield.kgha^{-1} ~						
Avg.PH	9.378	4.512	2.079	0.038*	9.378	0.287
Pod.clearance	9.345	11.198	0.835	0.404	9.345	0.064
Internode.length	23.29	40.049	0.582	0.561	23.29	0.054
Nodes	-19.23	27.741	-0.693	0.488	-19.23	-0.107
Seedspod^{-1}	87.841	71.737	1.224	0.221	87.841	0.102
D50F	-24.544	13.981	-1.756	0.079	-24.544	-0.169
DTM	-22.191	11.56	-1.92	0.055	-22.191	-0.234
Podsplant^{-1}	22.77	4.928	4.621	0***	22.77	0.635
X100SW	69.604	26.09	2.668	0.008**	69.604	0.333
Rust	-177.149	74.605	-2.374	0.018*	-177.149	-0.287
Branches	-87.426	41.128	-2.126	0.034*	-87.426	-0.241

***, ** and *** indicate significance at $\alpha \leq 0.05$, $\alpha \leq 0.01$, and $\alpha \leq 0.001$ respectively**

The path diagram (Figure 2) shows the direct and indirect relationships between the observed traits and seed yield. The direct relationships are indicated by the unidirectional solid lines while the indirect relationships are indicated by the bi-directional dotted lines. Significant and direct relationships are of darker shades of color than non-significant ones. The traits that had significant positive direct effect on seed yield were number of pods per plant, hundred-seed weight and average plant height. On the other hand, soybean rust score and number of branches had significant negative direct effects on the seed yield. Each of these traits that had a significant direct relationship with the yield had both direct and indirect effects as elaborated below.

Number of Pods per plant

Pods per plant had a significant positive effect on seed yield at $p < 0.001$ (Table 6). There was a positive relationship between number of pods per plant and average plant height, internode length, seeds per pod, nodes, branches as well as rust score. There was a negative relationship between pods per plant and hundred-seed weight (Figure 2).

Hundred-seed weight

Hundred-seed weight had significant positive effect on the seed yield at $p < 0.01$ (Table 6). There was a positive relationship between hundred-seed and internode length, average plant height as well as seeds per pod (Figure 2).

Average plant height

Average plant height had significant positive effects on the seed yield at $p < 0.05$ (Table 6). There was a positive relationship between average plant height and number of pods per plant, number of nodes, rust score and days to physiological maturity (Figure 2).

Rust score

Soybean rust score had significant negative effect on the seed yield at $p < 0.05$ (Table 6). There was a positive relationship between rust and number of nodes, pods per plant, hundred-seed weight, seeds per pod and average plant height (Figure 2). There was a negative relationship between rust score and pod clearance (Figure 2).

Branches

Number of branches had a significant negative direct effect on seed yield at $p < 0.05$ (Table 6). Branches had positive relationship with pods per plant and average plant height (Figure 2). On the other had there was a negative relationship between branches and traits that had positive effects on seed yield such as hundred-seed weight, pod clearance, and seeds per pod (Figure 2).

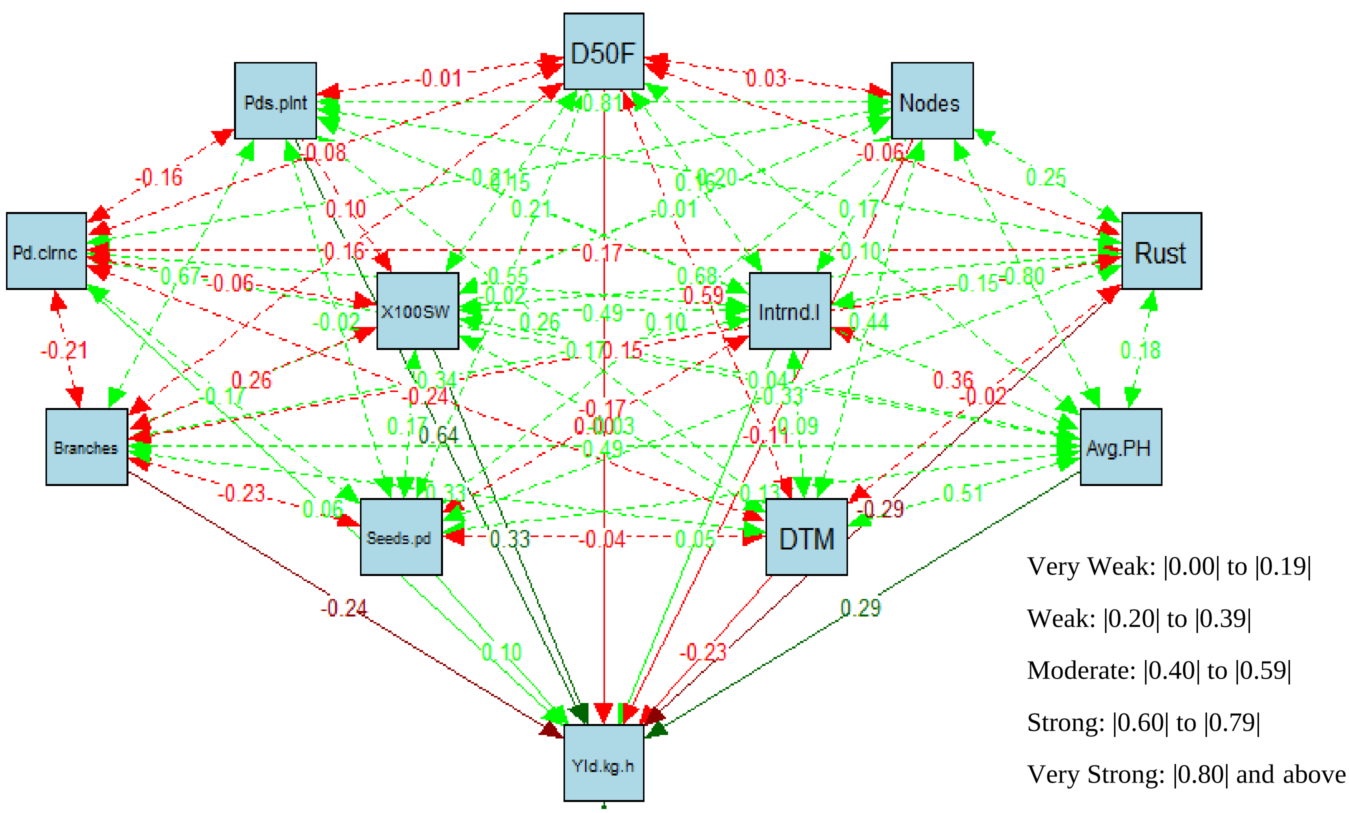

Figure 2: Path Diagram for the agronomic and yield-related traits

4.2 DISCUSSION

This study was conducted with the objective to assess the agronomic and yield-related characteristics of the sixteen genotypes at the Preliminary Yield Trial stage of the MAKSCID breeding programme. It was observed that the mean days to 50% flowering of 44.6 and range of 40.3 to 44.6 days was similar to other studies in Uganda (Tsindi et al., 2019) and outside Uganda (Mudibu et al., 2011; Qin et al., 2017). The days from flowering to maturity ranged from 50 to 60.7 which were lower when compared with other studies which have found maximums of 96 days (Sinegovskaya and Levina, 2021) and 85 days (Vlasova et al., 2023). This difference may be attributed to the genotypic characteristics of the materials used or the hotter temperatures in Uganda compared to the areas where those studies were conducted since higher temperatures accelerate the reproductive period (Gogoi et al., 2018). The range for days to physiological maturity was 93.7 to 107 days which is within the medium maturity category of 90 to 120 days after planting (Tukamuhabwa and Obua, 2015). These results are most probably due to breeding efforts by MAKSCID to meet their objectives of producing soybean varieties that mature within 120 days (Tukamuhabwa and Obua, 2015).

The average plant height found in this study was 81.4cm which was of medium range compared to studies outside Uganda (Diondra et al., 2008; Fletcher and Fisher, 2019; Mudibu et al., 2011) but well within the range of Maksoy varieties (Tukamuhabwa and Obua, 2015). The mean internode length of 7cm was higher than the 2.9cm and 3.7cm in the study by Oki et al. (2018). This difference might be because they were mapping the quantitative trait loci associated with short internode length in Japanese cultivars so their study was intentionally dealing with plants of shorter internode length. The mean number of branches was 1.7 with a maximum of 3.2 which was fewer than other studies that had up to 9.8 branches (Li et al., 2020) and 5 branches (Thio et al., 2022). The differences in these results may be because this study focused on primary branches while others considered both primary and secondary branches.

14.2 was the mean number of nodes found in this study and it is similar to results in other studies (Allen et al., 2018; Fahim et al., 2021). The mean pod clearance found of 9.8cm was in agreement with Beiküfner et al. (2019) who reported similar values for soybean grown in organic system, that is without artificial fertilizer which were similar to conditions in which this study was conducted.

There were three genotypes with average soybean rust score below 3.0 which showed more resistance to the disease compared to Obua (2013) whose lowest average score was 3.1. This is probably due to the genotypes in this study having less compatibility with the fungal pathogen *P. pachyrhizi* as shown by the reddish-brown lesions observed on the leaves (Goellner et al., 2010). The mean number of pods per plant was 31.4 which is comparable to results from similar studies (Kayaga, 2019; Mugisha, 2016). This study found significant differences among the genotypes for number of seeds per pod which is in agreement with Biswas et al. (2016) who characterized some genotypes of soybean in India and also found significant differences in the same parameter. The minimum number of seeds per pod was 2 seeds which is higher than some studies probably due to breeding efforts (Biswas et al., 2016; Księżak and Bojarszczuk, 2022). The mean hundred-seed weight was 14.2g which was slightly lower than results from other studies which all had means above 19g (Li et al., 2020; Mugisha, 2016; Qi et al., 2020). This lower hundred-seed weight may be due to mild water stress during the seed filling stage which occurred during late November to early December which experienced infrequent rainfall (Uganda National Meteorological Authority, 2023). The mean seed yield of the 16 genotypes was 1178 kg ha^{-1} which was comparable to the results of some other studies (Mudibu et al., 2011; Xu et al., 2022).

Another objective of this study was to determine the nature of the relationship between the agronomic and yield-related traits and seed yield. Of the eleven traits subjected to correlation analysis, six traits (54%) had a significant positive correlation with seed yield and these were hundred-seed weight, pods per plant, internode length, plant height, number of nodes and seeds per pod. This implies that when these traits increase, so does the seed yield.

The positive correlation found between hundred-seed weight and yield is in agreement with Belay et al. (2023) but contrary to the findings of Balla and Ibrahim (2017). In the study by (Balla and Ibrahim (2017), the soybean genotypes used had high fodder yield which was very highly positively correlated with seed yield but negatively correlated with hundred-seed weight so the results showed that seed yield increased with decreasing hundred-seed weight. Although the fodder yield was not assessed in this study, it can be safely assumed that it was low because the seed yield was positively correlated with hundred-seed weight and it was reported by Adams (1967) and Nemati et al. (2009) that fodder yield and hundred-seed weight are difficult to simultaneously select for due to their inverse relationship yet they can both positively contribute to seed yield. The positive correlation between seed yield and hundred-seed weight was exemplified by genotype 6N×Saga-P-3-1 which had the maximum hundred-seed weight of 19.9g and maximum seed yield of 2059.3 kg ha^{-1}. When ranked in descending order of yield, the top half of the genotypes (first eight genotypes in Table 5) all have 100SW above 14.0g. The yield from these genotypes ranges from 2059.3kg ha^{-1} to 1248.5 kg ha^{-1}. Meanwhile, the bottom half of the yield ranking had genotypes whose 100SW ranged from 10.0g to 15.0g. However, the genotype 8.11 × 2N-2A has a hundred-seed weight of 15g but wasn't among the highest yielding genotypes in this study. This may be due to low number of pods per plant (29.1) and only two seeds per pod.

The positive correlation between number of pods and seed yield means that higher the number of pods per plant, the higher the seed yield because more pods mean more seeds on a given plant. These results are in agreement with Yildirim et al. (2023).

The positive correlation found between plant height and seed yield is in agreement with Li et al. (2020) who found that taller plants gave higher yields in their study. This may be because taller plants have more nodes from which more pods arise and therefore more seed yield.

There was a positive correlation between internode length and seed yield meaning that the longer the length between two successive nodes, the higher the yield. This might be because longer internodes imply taller plants which have been correlated with higher yield (Allen et al., 2018). However, it is worth mentioning that long internodes make plants susceptible to lodging which has negative impacts on the yield (Xu et al., 2021). This study did not assess the lodging scores of the genotypes but the positive correlation between yield and internode length shows that the plants' internode length was not too high as to lead to lodging and affect yield.

The correlation analysis revealed a positive correlation between seed yield and the number of seeds per pod meaning that more seeds per pod is associated with more seed yield because there are more seeds to harvest within the pod. The genotype 6N × Saga-P-3-1 had the highest yield and 3 seeds per pod, which was the maximum.

Soybean rust score was negatively correlated with seed yield which is in agreement with many studies (Kumudini et al., 2008; Murithi et al., 2021; Pajo et al., 2018; Pivonia and Yang, 2004). This implies that the more resistant the genotype, the higher the yield as seen in genotype 6N × Saga-P-3-1 whose rust score was 1.7 and had the highest yield kg ha^{-1}. This is because soybean rust reduces the photosynthetic capacity of the leaf through decreasing leaf area and causing defoliation (Hoffmann et al., 2022; Kumudini et al., 2008).

The correlation analysis obtained a very weak positive correlation between number of branches and seed yield. Upon further analysis of the path coefficients, it was found that although there was a positive correlation between branches and traits that had high positive effects on yield that is, pods per plant and average plant height, the direct effect of branches on yield was negative and so was the relationship with the hundred-seed weight which counteracted the positive indirect effects of branch number. Xu et al. (2021) also found similar results using correlation analysis which showed that although pod number per plant increased with the increased branch number, it was important to select cultivars with weak branching ability to achieve higher yields because planting density was more impactful on yield yet negatively correlated with branch number.

Path coefficient analysis revealed that the traits with significant contributions to seed yield were number of pods per plant, hundred-seed weight, and average plant height in order of importance, making them key determinants of yield similar to the findings of Belay et al. (2023) and Li et al. (2020). Pods per plant had a significant positive direct effect on seed yield meaning that regardless of the other traits, high number of pods per plant led to higher seed yield.

The positive relationship between number of pods per plant and average plant height, internode length and seeds per pod indicated an indirect positive effect on the yield. However, these direct and indirect positive effects were counteracted by the positive relationship between number of pods per plant and nodes, branches as well as rust score which had negative effects on the seed yield. The negative relationship between pods per plant and hundred-seed weight also caused a decrease in seed yield. Hundred-seed weight had significant positive direct effects on the seed yield and this was enhanced by its positive relationship with internode length and seeds per pod since there was a positive relationship between these two traits and yield. Average plant height had significant positive direct effects on the seed yield meaning that taller plants had higher yields. Average plant height indirectly affected plot yield through the positive relationship with number of pods per plant. The positive relationship of plant height with nodes, rust score and days to physiological maturity led to a negative indirect effect on yield because of the negative effect of those three traits on yield.

The path coefficient analysis also showed that the soybean rust score negatively affected seed yield the most, followed by number of branches. Soybean rust score had significant negative effects on the seed yield meaning that plants with higher susceptibility to rust had lower seed yield. There was a positive relationship between rust and number of nodes which indirectly affected seed yield since nodes had a negative effect on yield. There was also a negative relationship between rust score and pod clearance, a trait which had positive effect on yield. The direct effect of rust score on yield was weak because rust had positive relationships with traits that had positive effects on yield such as pods per plant, hundred-seed weight, internode length, seeds per pod and average plant height. Number of branches had a significant negative direct effect on seed yield meaning that plants with more branches had lower seed yield. Branches had positive correlation with pods per plant and average plant height which both had significant positive effects on seed yield. On the other hand, there was a negative indirect effect of branches on yield due to the negative relationship between branches and traits that had positive effects on seed yield such as hundred-seed weight, pod clearance, and seeds per pod.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study found significant differences among the PYT genotypes for the traits days to 50% flowering, days to maturity, internode length, seeds per pod, hundred-seed weight, resistance to rust and seed yield.

All the genotypes were medium maturing between 93.7 to 107 days and soybean rust resistance varied from 1.7 for most resistant to 4.0 for most susceptible genotypes. The genotype 6N × Saga-P-3-1 had the highest yield of 2059.3 Kg ha^{-1}, was the most resistant to soybean rust disease and matured in 96.3 days making it the best-performing genotype in this study.

The seed yield was found to be positively correlated to hundred-seed weight, pods per plant, seeds per pod, internode length, average plant height, and nodes per plant. Rust score was negatively correlated with seed yield. Hundred-seed weight and number of pods per plant had highly significant positive correlations with seed yield implying that when their values were high, so was the seed yield.

The path coefficient analysis also showed that the traits with significant contributions to seed yield were number of pods per plant, hundred-seed weight, and average plant height in order of importance, making them key determinants of yield. The soybean rust score negatively affected seed yield the most, followed by number of branches.

Summarily, the results of the correlation and path coefficient analysis showed that increase in the number of pods per plant and the hundred-seed weight and while minimizing the susceptibility to soybean rust should be the major focus of breeders in order to achieve higher yielding soybean varieties.

5.2 Recommendations

The six genotypes whose yield was significantly higher than the check variety PYT 6N, are recommended for advancement to the Intermediate Yield Trials to further ascertain their superiority over existing varieties. These are 6N × Saga-P-3-1, 2N × 5N-2, 8.11 × 2N-4, Plot 117 PYT 2020B, 6N × Squire-C, and 6N × 2N-2-3.

The rest of the genotypes whose yield was below that of PYT 6N, that is genotypes Signal × 5N, SPS 6N × 2N-2, 8.11 × 2N-2A, 6N × 2N-2-4-2, G 7955 × 2N, 4M × 11.2-1, SPS BSPS 48A-28-1, and 4M × 14.1-24 should not be advanced to the next stage of the breeding programme.

When breeding for high-yielding varieties, the traits positively correlated with yield should be selected for. The most important traits that should be the focus of breeders to increase seed yield, according to the results of this study, are more pods per plant, higher hundred-seed weight, and taller plants. Based on hundred-seed weight, the two genotypes to select in this study were 6N × Saga-P-3-1 (19.9g) and 6N × Squire-C (16.3g). Based on the number of pods per plant, genotypes 6N × 2N-2-3 (49.1 pods) and 2N × 5N-2 (44.8 pods) should be selected. Based on plant height, genotypes 2N × 5N-2 and 8.11 × 2N-4 which had averages of 95.1cm and 93.7cm respectively are recommended for selection.

Internode length and seeds per pod can also be considered since they had a positive correlation with seed yield and counteracted some negative effects.

Traits that were negatively correlated to yield should be selected against. Therefore, plants that were more susceptible to rust should be selected against and those with low rust scores should be selected for that is genotypes 6N × Saga-P-3-1 (1.7) and 6N Selected (2.7). Even though genotype 4M×11.2-1 had one of the lowest seed yields, it was moderately resistant to soybean rust with a score of 2.7, and can therefore be considered for use as a breeding material for source of resistance genes.

Overall, the best-performing genotype was 6N×Saga-P-3-1 with maximum hundred-seed weight of 19g, 49.1 pods per plant, minimum rust score of 1.7 and highest yield of 2059.3 kg ha^{-1}.

Although pod clearance has zero correlation with yield in this study, literature showed that it is an important trait to breed for higher pod clearance to facilitate mechanization. More studies need to be conducted to study the correlation between pod clearance and yield with consideration of harvest losses.

It is recommended that multi-location studies are done with the genotypes that were assessed to study how the traits are affected by the environment and the genotype by environment interaction. There is also a need to conduct similar studies over more seasons.

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Appendices

NB; *, ** and *** indicate significance at α ≤ 0.05, α ≤ 0.01, and α ≤ 0.001 respectively

Appendix 1: ANOVA for Days to 50% Flowering

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
REP	2	3.4	1.687	1.584	0.222
GEN	15	368.5	24.565	23.06	1.99e-12 ***
Residuals	30	32	1.065		

Appendix 2: ANOVA for Days from Flowering to Maturity

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
REP	2	23.6	11.813	1.663	0.2065
GEN	15	392.6	26.176	3.686	0.00115 **
Residuals	30	213	7.101		

Appendix 3: ANOVA for Days to Maturity

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
REP	2	23.6	11.81	1.855	0.174
GEN	15	738.6	49.24	7.732	1.2e-06 ***
Residuals	30	191	6.37		

Appendix 4: ANOVA for Average Plant Height

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
REP	2	891	445.7	4.123	0.0262 *
GEN	15	3875	258.4	2.39	0.0206 *
Residuals	30	3243	108.1		

Appendix 5: ANOVA for Number of Branches

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
REP	2	0.68	0.3408	0.412	0.66595
GEN	15	39.71	2.6471	3.201	0.00325 **
Residuals	30	24.81	0.8271		

Appendix 6: ANOVA for Internode Length

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
REP	2	0.62	0.31	0.462	0.6344
GEN	15	25.39	1.6924	2.523	0.0151 *
Residuals	30	20.13	0.6709		

Appendix 7: ANOVA for Rust Scores

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
REP	2	0.292	0.1458	0.868	0.43
GEN	15	17.146	1.1431	6.802	4.59e-06 ***
Residuals	30	5.042	0.1681		

Appendix 8: ANOVA for Pod Clearance

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
REP	2	221.7	110.85	25.382	3.54e-07 ***
GEN	15	52.28	3.49	0.798	0.671
Residuals	30	131.02	4.37		

Appendix 9: ANOVA for Number of Nodes

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
REP	2	14.4	7.201	1.572	0.224
GEN	15	115.5	7.703	1.682	0.11
Residuals	30	137.4	4.58		

Appendix 10: ANOVA for Number of Pods per plant

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
REP	2	310	154.9	1.286	0.291
GEN	15	2740	182.7	1.517	0.161
Residuals	30	3612	120.4		

Appendix 11: ANOVA for Number of seeds per pod

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
REP	2	1.167	0.5833	3.621	0.0390 *
GEN	15	5.479	0.3653	2.267	0.0275 *
Residuals	30	4.833	0.1611		

Appendix 12: ANOVA for Hundred-seed weight

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
REP	2	0.92	0.46	2.098	0.14
GEN	15	188.86	12.591	57.464	<2e-16 ***
Residuals	30	6.57	0.219		

Appendix 13: ANOVA for Seed Yield

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
REP	2	248559	124279	1.241	0.3036
GEN	15	5310631	354042	3.534	0.00158 **
Residuals	30	3005057	100169		