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Evidence-Based Production Technologies for Improving Potato (*Solanum tuberosum*) Yields

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ABSTRACT

Potato is one of the most important food crops with a capacity to abate hunger among farmers in the region. However, its productivity has stagnated and remained low due to poor agronomic practices applied by smallholder farmers. To avert this situation, dissemination through training of already existing better technologies and practices should be prioritized. A lot of research has been done with better recommendations- use of disease-free tuber seeds from high yielding and tolerant varieties, adequate application of balanced nutrients, timely scouting and integrated management of pests and diseases and good harvesting practices are available for immediate adoption. The adoption and dissemination could be facilitated by currently existing policies that promote cross-border movement and diffusion of research technologies and new varieties.

***Keywords*:** Bacterial wilt, disease management, Late blight, nematodes, potato tuber moth, potato virus, integrated pest management, *Solanum tuberosum*, weed management

1. INTRODUCTION

Potato (*Solanum tuberosum*) is one of the most important crops in East Africa with potential productivity of over 25 t/ha under optimum agronomic practices (Al-Dalain, 2009). The crop has the potential to abate hunger and increase the economic status of farmers due to its fast maturity period (usually 60-90 days) and higher yield per unit area of land compared to

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maize (UARC, 1990). According to the International Potato Center (CIP), one hectare of potatoes can yield 2-4 times the food value of grain crops and produce more food per unit of water than any other major crops and seven times more efficient in using water than cereals. Despite such high food value and economic sense, Irish potato yields are still low and stagnate at 5, 9.1 and 5.8 t/ha compared to the achievable farmer yields of about 20 t/ha in Tanzania, Kenya and Uganda respectively (Gildemacher *et al.*, 2009; Namwata *et al.*, 2010). Such low yields may be linked to the application of poor agronomic practices in the region. The main producing zones include Njombe, Iringa, and Mbeya regions in Tanzania (Namwata *et al.*, 2010); Mt. Kenya region, Central region, Central Rift region, North Rift region in Kenya (Gildemacher *et al.*, 2009; Were *et al.*, 2013); and Kabale and Kisoro districts in Uganda (Bonabana-Wabbi *et al.*, 2013). Therefore, this review aimed at highlighting potential technologies available for improving potato yields in the East Africa region.

2. SUITABLE CONDITIONS AND PRACTICES FOR POTATO PRODUCTION

Field selection is a crucial step in ensuring that the crops are grown under suitable climatic and edaphic conditions. The practice also ensures early management of pests and diseases as fields with already high incidences of pests and diseases are not considered. For effective field selections, farmers are expected to keep proper records on the occurrence of important pests and diseases on the farms, past soil fertility management and cropping systems.

Irish potato being a high altitude crop, a range of 1200-2400 m above sea level should be considered appropriate for its production though it is still possible to produce it in low altitudes as long as the cultivation periods are accompanied by low temperatures. In terms of temperature requirement, cool night temperature range of 18 to 35 ^{0}C is considered ideal (Papademetriou, 2008). Rainfall and water requirement by potato crop vary depending on the variety and stage of growth. According to Yara International, for instance, the crop requires 1 mm of water per week during tuber bulking and should be reduced towards maturity. Generally, an annual rainfall amount of between 500 and 1000 mm during the production periods is required (Zemba *et al.*, 2013). Depending on the financial capability of the farmer, this water could come from either rainfall or irrigation or both. In terms of soil conditions, deep, well-drained and friable soil types are the best (e.g. loam, sandy-loam, and sandy-clay types). Friable soils provide good conditions for free expansion of tubers during development. Slightly acidic soil (pH 5.5-6.5) with high organic matter is required for better growth and productivity.

3. LAND PREPARATION AND RIDGING PRACTICES

Land preparation is one of those important practices in potato production. The practice should be done early enough in the dry season to allow for proper control of weeds, diseases, and burrowing pests. The weed seeds, burrowing pests, and disease pathogens are exposed to predators and desiccation by the heat from the sun during plowing leading to early control. Depending on soil type and compaction of the soil layers, deep tillage of about 30 cm in depth during primary and first secondary tillage should be done for better soil water infiltration and root development. Use of raised beds of 4-6 rows separated by a furrow is applicable in farms experiencing waterlogging as with the case of heavy black soils and relatively flat topography. Planting on ridges in flood-prone areas have been associated with yield increase (Njoroge, 1984).

4. SELECTION, PREPARATION, AND TREATMENT OF PLANTING MATERIALS

Selection of planting materials is an important practice in potato production because it offers farmers prior opportunity to determine yields, pest and disease control, and market value of the products.

From the agronomic contexts, potato seed (also known as tuber seed) refers to the vegetative part of potato (tuber) used for propagation. It should be understood that the use of sexual seed (also known as true potato seed (TPS)) is also possible. Currently, the use of sexual seed has a lot of attention globally due to its benefits in disease control, easy storage, and transportation (Chujoy & Cabello, 2007; Almekinders *et al.*, 2009; Czajkowski *et al.*, 2011). Though the technology also has its own fair share of challenges- complicated to cultivate and requires a lot of attention particularly during germination; the plants generated from TPS are prone to pest and disease attacks; the technology requires specific training in terms of handling and storage and breaking of seed dormancy; the seeds have poor germination and plants take a longer period to reach maturity with some displaying unusual characteristics (as they are not true-to-type crops) (Gaur *et al.*, 2000; Muthoni *et al.*, 2013).

The initial steps in the control of potato pests and diseases and the realization of better yields start with proper selection of planting materials. This means that seeds should come from superior and healthy mother plants. Therefore, careful selection of varieties is important for improved economic returns- productivity and market value. Qualities of good planting materials are as summarized in Table 1.

Table 1. Summary of physical quality attributes to be considered when selecting tuber seeds for planting.

Character / Quality	Description of the better seed tubers
Origin and mother plant	Seeds should be obtained from pest and disease-free mother. To achieve this, farmers should always select and store seeds harvested from healthy mothers (as under farmer-saved seeds) or buy seeds from certified seed producers.
Shape and physiques	Egg-shaped tuber seeds are preferred. The seeds should also be without holes, cracks, and signs of pest and disease attacks. Farmers should completely reject the seed lots with more than 10% tubers with soft spots that ooze with fluids when pressed since this could be a sign of Bacterial wilt attack.
The skin appearance	Fresh and unwrinkled seeds are preferred. A wrinkled tuber is a sign of dehydration and a possible reduction in vigor and germination viability. For planting purposes, even the greened tubers can be used.
Weight and size	Small potato tubers are preferred- weights of between 30 and 80 g should be selected for planting (Barry *et al.*, 2001; Papademetriou, 2008). It has been found that small to medium seeds produce few but large tubers with high market value compared to large to very large seeds (Wurr *et al.*, 1993; Love & Thompson-Jones, 1999; Khan *et al.*, 2010).

	In the case of large tubers, farmers should cut them into small sizes. During the splitting process, care must be taken to avoid contamination and infection with diseases that could be transferred into the fields. Farmers should, therefore, use sterilized and disinfected knives for cutting the larger tubers to avoid contamination.
Number of eyes and sprouts	Each planting material should have at about 2-10 eyes/buds- these are areas where shoots emerge. These buds should be distributed spirally around tuber surfaces. In the case of chitted tubers, the sprouts should be uniform in lengths and color.

Proper seed preparation and treatment before planting is very important in ensuring quick and uniform germination and reduction of possible chances of pest and disease attacks. In the East Africa region, planting of potatoes is usually done either during dry and warm periods (dry planting) or warm and moist conditions (wet planting).

Table 2. Summary of key treatments and procedures recommended when preparing tuber seeds before planting.

Practice	Description	Rationale
Warming	Warming is practiced on seeds stored in low temperatures < 4 ºC. The cold tubers are warmed at 16 ºC for about 1-2 weeks before planting.	Low temperatures condense moisture on the skin surfaces leading to seed decay.
Cutting/splitting	Splitting of tubers is suitable for large seeds weighing between 85g and > 200g. Such seeds are cut into 2 and 3 seeds respectively.	Tubers weighing between 85 and 200 g have either many eyes which may produce many stems per hill or likely to produce blind seeds.
Curing	Curing is the process of allowing the sap to drain and wounds to seal off before planting. This should be done for 3-4 days under shade before planting.	Wet and un-suberized surfaces attract soil-borne pathogens and may cause decay. If left in direct sun heating, the seeds may become dehydrated and lose viability.
Chitting	Chitting is the process of inducing sprouting of potato seeds before planting. It is done by exposing seeds to warm temperature and much light. Also, seeds could be treated with the gibberellic chemical at 5-10 ppm to speed up sprouting.	The practice helps in breaking tuber dormancy and encourages uniform and faster establishment. Also, it encourages the production of early crops in the season.

Removal of apical dominancy	This is the removal of buds that may have sprouted and developed before others. Apical dominance causes other buds to delay in sprouting or fail to develop completely.	Apical dominance results in single stem per hill, hence low yield per unit area.

Table 3. Some of the main varieties of Irish potato grown by farmers in East Africa region. When selecting better varieties, farmers need to consider some of these traits listed here.

Key traits to consider	**Some of the selected varieties**					
	Asante	**Sherekea**	**Uyole**	**Meru**	**Tengeru**	**Tigoni**
Altitude range (m.s.l.)	1200 >	1800-3000		1200-2900		1800-2600
Yield (t/ha)	35-45	40-70	25-30	35-50	30-40	35-45
Tubers per plant	high	high	low	high	moderate	high
Dry matter	high	high	high	high	high	high
Maturity	short	medium	medium	medium	medium	medium
Tuber skin colour	pink	red	n/a	n/a	n/a	white
Eye depth	shallow	medium	n/a	n/a		shallow
Tuber dormancy	short	long				short
Tuber shape	round	oblong	n/a	n/a	n/a	oval
Cooking quality	good	good	good	good	good	good
Resistance to Late Blight	yes	yes	yes	yes	yes	yes
Resistance to lodging	yes	yes	n/a	n/a	n/a	moderate
Resistance to viruses (X, Y, leaf roll)	yes	yes	n/a	yes	n/a	susceptible
Storability	poor	good		n/a	n/a	poor

5. SOWING AND CROPPING SYSTEM

Potato farmers from the East Africa region carry both dry and wet planting of the crop depending on the timing of rainfall, labor availability and conditions of the tubers- only pre-sprouted tubers are wet-planted. Farmers who use pre-sprouted tubers, therefore, need to pay much attention to weather forecasting since any failed rain after planting may cause drying up of new sprouts and consequently low plant density and high cost of gapping. When planting pre-sprouted tubers, the eyes/sprouts should be placed facing upwards for faster and uniform germination. No specific planting time is required when crops are produced under irrigation system.

Recommended potato plant density is influenced by variety and growth characteristics, soil moisture, soil fertility, purpose, and required tuber sizes (narrow spacing results in small tubers). The impact of increasing the density of potatoes on yields is not direct as researchers have reported mixed results. For instance, Gulluoglu & Arioglu (2009) reported a decrease in yield due to narrow spacing, an effect they attributed to competition for growth factors. In contrast, Thompson-Johns (1999) and Strange & Blackmore (1990) observed increased yields. This increase in yields was attributed to the increased number of plants per unit area and tubers per plant according to Khalafalla (2001). Therefore to avoid the risk of depressed yields due to competition for growth factors, farmers should adopt the recommended spacing from the breeders and agronomists. Across East Africa region, the inter-row spacing of 75-90 cm and intra-row spacing of 35-15 cm has been recommended for the varieties produced (Masarirambi *et al.*, 2012). For better sprouting and establishment, tubers should be placed at a depth of 10-15 cm planting. In terms of cropping systems, potatoes should be planted in a pure stand in rotation with non-Solanaceae crops (like maize, peas, and beans) after every 1-2 seasons. The period of rotation depends on land availability and the rate of pest and disease build-up- the longer the period of rotation the better the control. Intercropping of potato with cereals, as sometimes practiced in the region, is also marked with mixed impacts- both reduction and increase in yields depending on the density of the crops, planting pattern, and stage when the intercrop is introduced after potatoes. For instance, Begum *et al.* (2016) concluded that high potato yields and economic advantage is realized when hybrid maize is sown 30 days after planting potato. On the other hand, Sharaiha & Saoub (2004) and Kidane *et al.* (2017) reported a 61% decrease in potato yields when intercropped with maize. Again, for farmers to manage competition for nutrients, which is likely to occur between maize and potato plants, they would be required to apply large quantities of fertilizer for both the crops- a practice likely to demand high financial support from already resource-constrained farmers. Therefore if enough land is available, planting potatoes in pure-stand would be the best practice.

6. FERTILIZER APPLICATION AND SOIL FERTILITY MANAGEMENT

Potatoes, like other crops, require an adequate and balanced supply of nutrients for better growth and tuber yields. The crop is very sensitive to low nutrient levels (especially N, P and K nutrients) that affect the vegetative phase and severely reduce tuber yields at the bulking stage. In terms of nutrient removal, the crop removes about 4 kg N, 0.6 kg P, 6.5 kg K, 0.1 kg Ca and 0.35 Mg kg, 0.0034 kg B, 0.003 kg Cu per ton of tubers harvested (Beukema & Van der Zaag, 1990).

The crop greatly responds to N application with better N utilization coefficient achieved at 120 kg N/ha (Ruža *et al.*, 2013). Other researchers have recommended 150 kg N/ ha to be optimum and economical (Adhikari, 2009). This means that 120-150 kg N/ha is appropriate for farmers who have not carried out soil testing in recent years. But care must be taken to avoid over-application (above 150 kg N/ha) that promotes excessive vegetative growth over tubers and lower the quality and taste of tubers when cooked (Goffart *et al.*, 2008; Ruža *et al.*, 2013). Figure 1 shows graphical tuber yield response to various rates of nitrogen rates across various countries. To allow for better recommendations within the economic levels, farmers should always test their soils for available N, organic matter content and the capacity to release the required amounts. Also, N fertilizers should be applied in splits during topdressing to reduce losses from leaching, volatilization, and erosion processes.

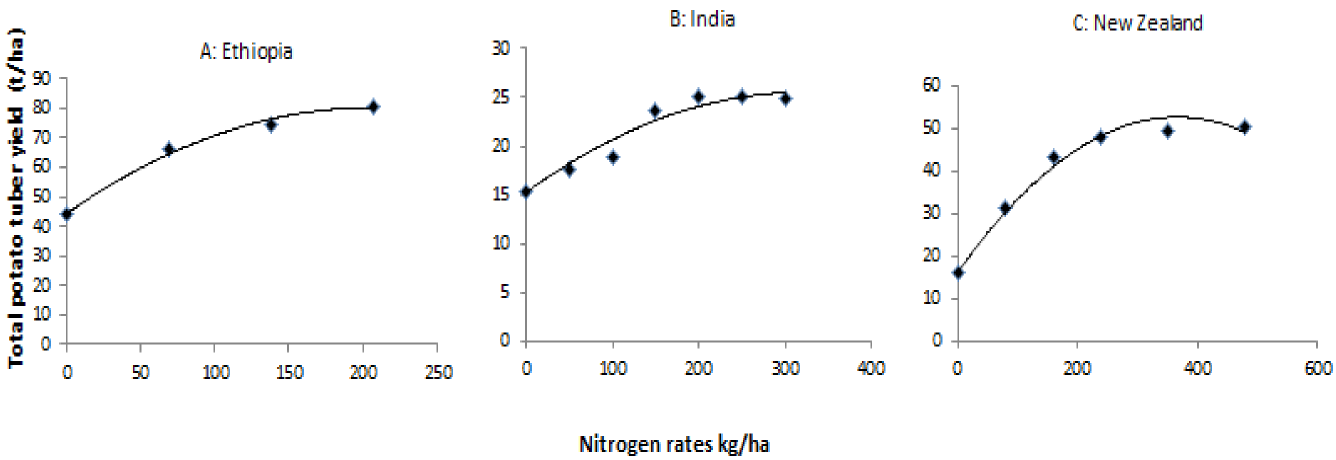

Figure 1. A graphic presentation of potato tuber yield response to different rates of nitrogen in Ethiopia, India and New Zealand. On average, the crop achieved highest yields at about 150 kg N per hectare. Data extracted from Craighead & Martin, 2003; Zelalem *et al.*, 2009; Sriom *et al.*, 20017.

Phosphorus is another important nutrient for potato growth and tuber production with a daily intake of up to 1 kg/ha/day occurring, mostly, between 30 and 45 days after emergence (Horneck & Rosen, 2008). The crop has a higher requirement for nutrients than other plant species but very low P-use efficiency (Munoz et al., 2005). This condition could lead to high fertilizer application rates that do not necessarily result in a high return on investment. Research by Rosen *et al.* (2014) seems to suggest that rate up to 200 kg P_2O_5/ha depending on fertility status could be appropriate for improved yields (Figure 2). However, researchers seemed to settle at 45 kg P (103 kg P_2O_5)/ha to be economical (Ekelof, 2014; Zelalem *et al.*, 2009; Nyiraneza *et al.*, 2017). Basal application of P fertilizers is encouraged to provide the much-needed nutrients for better growth and development of roots and tubers.

Potassium is also a very important nutrient for potato production as it plays key roles during growth and tuber development. The benefits of K nutrient are realized even at the table-as it is believed to help in improving the color of the final fried products (Perrenoud, 1993). At the critical high demanding (around bulking) stage, potato daily K requirement gets to as high as 5.6-15.7 kg/ha (Horneck & Rosen, 2008). Hence needs to be applied adequately at 4-5 weeks after planting to reduce leaching losses and make nutrients available at the bulking stage. Potatoes have luxury consumption of K nutrient leading. This could lead to mixed yield responses and quality attributes when the rates exceed 250 kg K/ha (Allison *et al.*, 2001; Craighead & Martin, 2003). According to Karam *et al.* (2011), the optimum K application rate should be about 150 kg/ha and any addition K above this could cause non-significant yield increase. In Ethiopia, 69-103 kg K/ha was found to be economical and result in high tuber yields (Shunka *et al.*, 2016). Again the efficiency of K is greatly influenced by the time of application- tuber vegetative versus tuber initiation versus tuber bulking phases. Karam *et al.* (2011) consistently recorded higher yields when K is applied during bulking compared to when applied at the tuber initiation stage. This means that high K rates should be top-dressed during this stage for better yields.

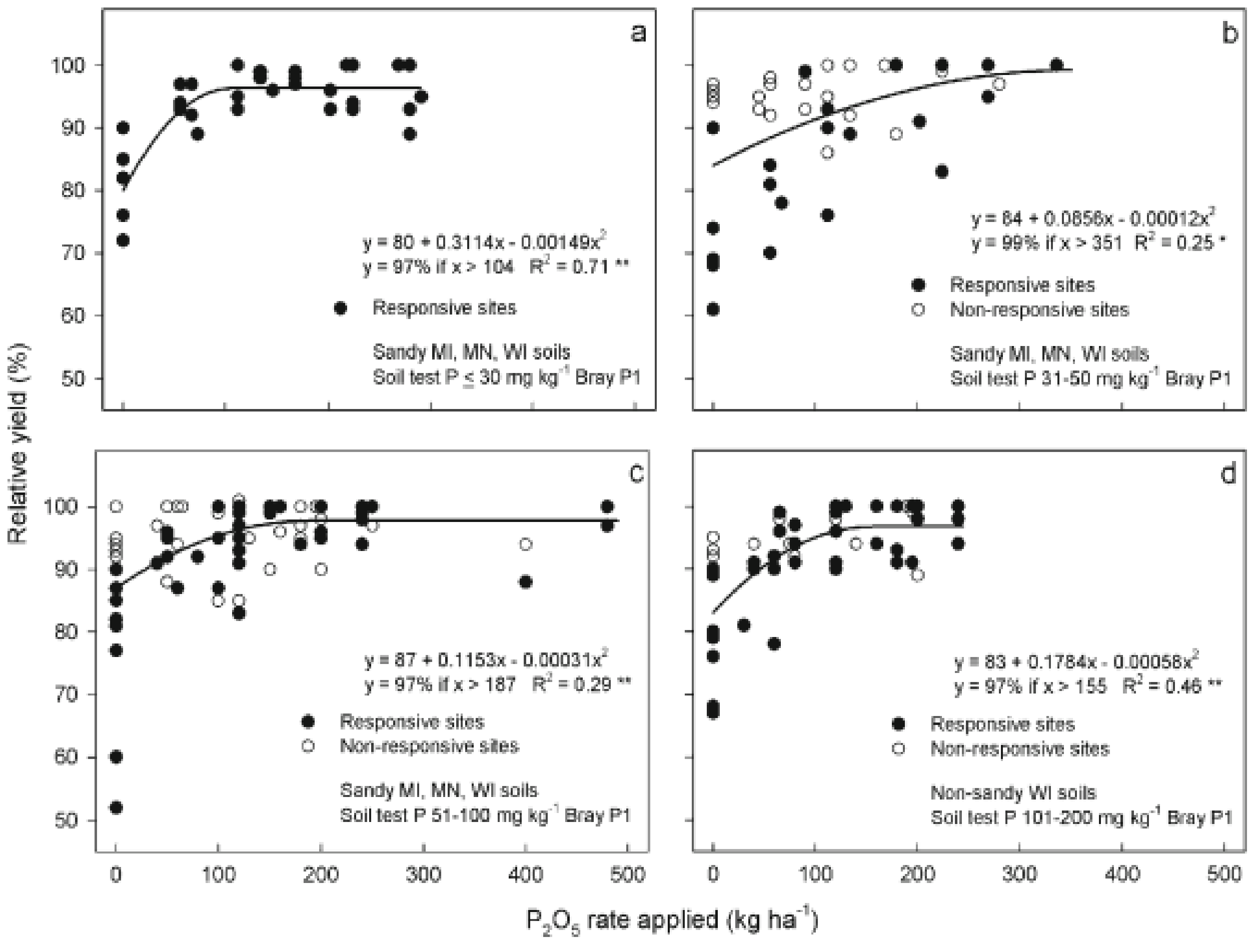

Figure 2. Relative total tuber yield as affected by phosphate fertilizer rate for Midwest soils with various soil textures and soil test P levels. Response set at a minimum 10 % yield increase. Source: Rosen *et al.*, 2014.

Calcium (Ca) and Magnesium (Mg) are also among the most important secondary nutrients required for better potato yields. These nutrients play major roles in photosynthesis and transportation and storage of photosynthates and tuber bulking. Hence, significantly influence potato yields and quality. For instance, according to Yara International, potato yields could be reduced by up to 15% due to severe Mg deficiency. Low levels of magnesium will reduce the starch content of tubers and protein levels thereby negatively affecting the taste of the cooked potatoes (Snacks, 1992). The optimal yield response and economic optimum rates of Mg application have been reported to be about 13 kg/ha (Talukder *et al.*, 2009). Calcium plays important roles in potatoes: Strengthening of the tuber cell walls thereby reducing soft rot incidences, and increase heat tolerance and minimizing wilting and leaf damage. All these could increase yields by up to 30% (Bussan *et al.*, 2007).

Based on the reported high nutrient removal rates per unit weight of harvested tubers, farmers need to adequately supply these nutrients. Various organic and inorganic fertilizer rates and compositions have been recommended across the region: In Kenya, Kenya Agricultural & Livestock Research Organization (KALRO) - Tigono recommends that farmers apply nitrogen and phosphorous at 90 and 230 kg per hectare in the form of diammonium phosphate (18:46) for potato production (Gildemacher *et al.*, 2009). This recommendation lacks K, Mg and Ca nutrient due to the perceived large soil reserve in the country. In Tanzania, a rate of between 150 and 300 kg NPK-23:10:5 has been found to increase yields and have better returns on investment in major potato growing areas (Shaaban & Kisetu, 2014). The crops also require soil organic matter for improved nutrient use efficiency and soil water conservation. Application of manure at 5-10 t/ha is commonly practiced for various crops in the region and have reported better tuber yields (Linus *et al.*, 2004; Muthomi & Kabira, 2011). Actually, farmers have been reported to prefer manure over inorganic fertilizer due to its greater yield responses (Tadesse *et al.*, 2017). Combined application of fertilizers with manure gives better yields than inorganic fertilizers alone. Hence could be prioritized when available at high quality.

7. EARTHING-UP

Earthing-up (also known as hilling) is the practice of heaping soil around the based on potato plants during production. It keeps the plants upright and the soil loose, prevents insect pests such a tuber moth from reaching the tubers; and helps prevent the growth of weeds (Papademetriou, 2008). At tuber formation stage, earthing-up helps to reduce the greening effect that reduces the quality of French-fries potato (Kouwenhoven *et al.*, 2003). This practice could be achieved during weeding by hilling-up soils around the bases of plants to about 20-30 cm high in the first weeding and 30-40 cm high in the second weeding. Both ridging and raised beds play significant roles in regulating soil water content for better growth and yields of potatoes.

8. BIOTIC STRESS CONTROL IN POTATO FIELDS

Biotic stress in potato production refers to any damages caused by living organisms. These living organisms could be largely grouped as bacteria, viruses, fungi, parasites, insect pests, and weeds. This category of constraint poses a major threat to crop production due to the favorable warm-wet and humid conditions experienced along the tropics leading to high multiplication and infestation in East Africa.

8. 1. Weeds management

Weeds are important biotic stress in potato production as they compete for growth factors and act as alternate hosts for pests and diseases. The economic importance of weeds could be grouped as (a) Direct effect- Weeds causing between 15-85% yield loss in potato fields depending on the types of weed flora, their density and duration of the crop-weed competition (Jaiswal & Lal,1996). This reduction in yield is due to competition for growth factors- space, nutrients, light, and water; and (b) Indirect effect - weeds acting as alternate hosts for pests and diseases. For instance tomato, pepper, and nightshade host Potato Spindle Tuber Viroid, potato virus X, S and Y, and blight diseases (Binyam, 2015). With all these, therefore, proper timing of weed control is crucial in realizing better yields in the region. Proper weed management should be done within the critical period of weed control- this is the period during potato growing season when weeds need be removed in order to prevent crop losses. This period has been reported as from planting until 25 days after flowering in potatoes (Ahmadvand *et al.*, 2009). Labor availability is increasingly becoming a common problem in the region and therefore farmers should avoid unnecessary weeding. When to weed potatoes should be dictated by weed population, crop tolerance level, prevailing weather conditions, and weed species. Proper timing within the yield-determining periods may reduce frequencies and costs incurred. From an economic standpoint, two weeding regimes at 30 and 50 days after emergence is optimum for the realization of better yields.

Depending on the financial capacity, scale of production and literacy levels, farmers may decide to do:

a) Mechanical weeding- this involves the use of farm tools and implements, mainly hand hoes, to carry out weed control.
b) Chemical method- this involves the use of selective herbicides for weed control.
c) Cultural method- such as proper selection and preparation of fields, optimum plant density, and mulching. The use of herbicides should be carefully done - the process selection to be based on toxicity to humans and other organisms, the selectivity, and efficacy and phytotoxicity levels.

8. 2. Management of common potato pests and diseases

Production of potatoes is affected by a number of insect pests and diseases causing both direct and indirect yield losses in the region. The general pest and disease management strategy involves proper implementation of integrated pest management (IPM) - a broad-based approach that integrates practices for economic control of pests in the most promising and environmentally safe option. The use of synthetic pesticides under IPM should be done with great care and only in situations where other available strategies have proved ineffective or under emergency cases. These should be of low human and ecological toxicity levels. This section, therefore, provides a summary of practices recommended for the management of these pests and diseases. Among others, broad-spectrum strategies include;

- Proper and timely monitoring and scouting: The frequency of scouting depends on the pest/disease, crop, weather, and stage of growth. Better scouting process ensures early detection and execution of appropriate control strategy. During field scouting, farmers should move in a traverse using the “W” pattern to identify any signs of attack. In situations where the farmer is not familiar with the pest and disease identified, it is advisable to reach out to community-based entomologist or pathologist for proper identification.
- Adoption of better cultural practices: Practices such as proper field selection and field sanitation are crucial initial steps towards the management pests and diseases. This means that proper keeping of farm history records (on diseases and pests) is required for better field selection.

- Use of certified disease and pest free seeds: During production, farmers need to select seed tubers from healthy mothers, as with the case of farmer-saved seeds, or purchase seeds from certified dealers to reduce chances of spreading these pests and diseases. Again, farmers need to reduce the period of recycling seeds to reduce disease buildup.
- Practice legume-brassica-potato-cereal rotation system: Crop rotation has been widely accepted as a means of keeping potato pathogens below economic thresholds. The common control mechanisms include breaking of the lifecycle of pests/pathogens as they are starved to death during the seasons when the host crops are not planted and acting as repellants to these pests. In addition to the control of these pathogens, the program also improves soil fertility through nitrogen fixation and soil organic matter buildup.
- Use of well-decomposed manure: Use of partially decomposed manure/compost derived from plant materials especially crops residues previously infected by diseases could provide a route for reinfection as pathogens are potentially transferred back into the fields. Therefore, proper composting of organic materials including potato residues to kill pathogens and pests before applying back into the farm as manure should be considered.

8. 2. 1. Management of important potato pests

Potatoes are affected by a number of insect pests causing both direct and indirect yield losses. Scouting for the presence of these pests is necessary and forms the basis of any sustainable and economical management strategy. In potatoes, scouting for caterpillars could be done weekly from emergence time to 30 days after emergence. Scouting for whiteflies, aphids, and thrips could be done throughout the vegetative phase when crops are mostly attacked while for millipedes and tuber moths to be carried out during tuber bulking stage (Otieno, 2019).

Nematode (*Meloidogyne* spp)

Specific nematode management practices for adoption include treating tuber seeds treatment with hot water before planting (Youssef, 2013). Use of antagonistic plant species such as *Crotalaria spectabilis*, *C. juncea*, *Tagetes patula*, *T. minuta*, *T. erecta*, *and Estizolobium spp* could be adopted in the potato farms to keep away the pest (Embrapa, 2015). Rotating potato with barley is effective in controlling *Globodera rostochiensis* and has reported up to 87% reduction in attacks (Senasica, 2013). Application of products developed from microorganisms such as *Pochonia chlamydosporia*, *Bacillus firmus*, *Paecillomyces lilacinus*, and *Trichoderma* spp. with the capacity to attach and parasitize on the nematode or eggs leading to their death have been recommended (Castillo *et al.*, 2013). Under heavy buildup of nematodes, application of chemical may be necessary: Chemicals such as methyl bromide, Aldicarb, fenamiphos, oxamyl, 1, 3 dichloropropene (1, 3-D), dazomet and metam-sodium have been found to offer control (Onkendi *et al.*, 2014). However, care must be taken during the application process as some of these compounds are very toxic to humans and other beneficial organisms.

Cutworm (*Agrotis* spp)

Cutworms could be controlled physically by collecting and killing. The practice could be aided by the use of rice brans placed strategically in the field to attract the worms which are then collected and killed. The crops could also be sprayed continuously with neem leaves or seed extracts for an eco-friendly control (Campos *et al.*, 2016). Use of synthetic chemical compounds such as Chlorpyriphos 20 EC at 2.0 kg/ha, quinalphos 25 EC at 2.0 kg/ha are also effective (Tripathi *et al.*, 2003). Poison baits (Dipterex +Sugar + Rice husk) have also proved effective- these baits are placed strategically on permanent plots of potatoes where they attract and kill the worms that feed on them (Shakur *et al.*, 2007).

Potato aphids

The population of these aphids can be regulated naturally by common enemies such as ladybird beetles, both adult and grub and syrphid larvae in potato fields (Tschumi *et al.*, 2016). To encourage survival and multiplication of these natural enemies, farmers should avoid using broad-spectrum pesticides that may kill them. Also, farmers could attract these natural enemies into their farms by planting nectar-producing edge plants around the farms. Under heavy infestation, pesticides could be sprayed to reduce the population: Use of biopesticide (e.g. *Lecanicillium longisporum* (Vertalec®), and *Lecanicillium attenuatum* (CS625) (Kim *et al.*, 2007); plant extract (e.g. Azatrol (1.2% azadirachtin), Triple Action Neem Oil (70% neem oil) and Pure Neem Oil (100% neem oil) (Shannag *et al.*, 2014); and synthetic formulations (e.g. phorate 10G, carbofuran 3G, acephate 75SP, lindane 6.5 WP) (Konar & Paul, 2005) have been found to be effective and recommended for the control.

Thrips

The effects of thrips are highly influenced by the health status of potatoes. Therefore, adequate water and nutrients supply are highly recommended. Use of reflective mulches (silver polyethylene and pieces of cardboard with aluminum foil) to illuminate underneath of leaves has been found to help in repelling these insects (Riley & Pappu, 2000; Lal Bhardwaj, 2013). The repelled pests are no longer hidden underneath, hence easily reached during the application of chemicals. The hiding behavior of thrips makes it difficult to achieve effective control with chemicals. Some of the chemicals recommended include *Azadirachta indica* (azadirachtin at 0.03% EC), and imidacloprid formulations (Anuj, 2009).

Potato tuber moth (*Phthorimaea operculella*)

This is the most important pest attacking potatoes both in the field and store. The pest could be controlled naturally by natural enemies (e.g. wasps and Larvae of lacewings, big-eyed bugs, some beetle species, etc.) which prey on the larvae of tuber moth (Symington, 2003). Cultural management practices such as deep planting (10-15 cm) coupled with 2-3 hilling during growing periods and irrigation to reduce cracks on the soil surface during dry periods have been found to reduce the attacks (Hanafi, 1999; Clough *et al.*, 2010).

Also, the moths could be repelled from the farm by applying rice straw mulch mixed with neem leaves 4 weeks to harvesting. Farmers could also practice improved cropping- intercrop potato with pepper, onion or peas and rotation with non-*Solanaceous* crops help to break the life cycle of the moths thereby reducing their population (Lal, 1991). Use of plant-extracts like oil from neem and sunflower seeds could reduce storage losses to 25% (Salem, 1991). However, care must be taken to avoid over-application of these products that may lead to tubers turning black and becoming flaccid resulting in low market quality.

The use of synthetic chemical products could be less effective once the pests are inside the tubers. However, timed application of neem leaves extracts, *Bacillus thuringiensis*, fenvalerate, methamidophos, and methomyl products have been found to have significant control (Kroschel & Koch, 1996; Rondon, 2010).

8. 2. 2. Management of important potato diseases

Diseases are the most important component of biological constraint affecting both above and below ground potato parts. Once in the tubers, the pathogens continue to develop and multiply even after harvest leading to total yield loss. Therefore scouting for fungal, viral and bacterial diseases should begin immediately after the emergence of sprouts and continue until harvesting to ensure disease-free tubers are harvested (Otieno, 2019).

Early blight (*Alternaria solani*)

The control of Early blight disease is difficult due to the huge amounts of secondary inoculum produced and capacity to survive in the soil (Campo *et al.*, 2007; Pasche *et al.*, 2004). The disease is soil-borne and could easily be dispersed by irrigation water. Therefore, farmers should regulate and avoid splashing water onto the leaves (Olanya *et al.*, 2009). At harvesting, farmers should avoid causing injuries on tubers that could cause the spread. Potato stores should be cool and promote rapid suberization of bruised and cut parts to keep away the pathogens (Tsedaley, 2014). Chemical application is also feasible- use of propineb, metalaxyl-M, and difenoconazole, and mancozeb products from 30 days after planting has been found effective (Horsfield *et al.*, 2010).

Late blight (*Phytophthora infestans*)

Adoption of tolerant varieties provide a sustainable strategy of managing the impact of Late blight and promising accessories have so far been identified for further breeding (Namugga *et al.*, 2018). Proper irrigation management through drip or furrow systems that minimize wetting of leaves is important in disease management. Chemical control should be used cautiously and only under heavy attack and emergency cases. Some of the chemical products recommended for use in the region include the application of fluazinam, Iprovalicarb+Propineb, mancozeb+metalaxyl-M, and mancozeb based fungicides (Nyankanga *et al.*, 2004; Haq *et al.*, 2008; Rahman *et al.*, 2008). The application rates and frequencies should be as directed on the product label.

Common scab (*Streptomyces scabies*)

The incidence of Common scab is influenced by soil pH, though the extent and optimum levels is a topic for further debate. Based on available data, most researchers have leaned towards alkaline conditions to reduce disease incidence and yield losses but this needs to be done cautiously without affecting the next crop in the subsequent season (Waterer, 2002). Use of manure has also been floated as a strategy for the management of scab disease (Conn & Lazarovits, 1999; Singhai *et al.*, 2011). This could be, in part, due to the ability of manure to raise soil pH and attract natural enemies (Otieno *et al.*, 2018). But the optimum rate of application is not clear and is likely to be affected by the quality and availability.

Verticillium wilt (*Verticillium albo-atrum / V. dahlia*)

Managing Verticillium wilt disease is challenging due to the wide number of host plants that exist at any given time in the farmer fields. However, crop rotation with cereals and non-host plants could break the life cycle of the pathogen and reduce the impacts. The period of rotation varies between 2 and 4 years according to Larkin *et al.* (2011). Under irrigation system, farmers are required to maintain soil moisture at 70-75% during the vegetative stage and 80% during tuberization to reduce the amount of infection (Powelson & Rowe, 2008; Johnson & Dung, 2010). Soil fumigation with products such as Metam sodium has been recommended though the efficacy is highly influenced by soil type, temperature, physical properties, pH, and water holding capacity (Woodward *et al.*, 2011). Again, the fumigation is an expensive practice and exposes farmers to highly toxic compounds. Biological control using bacterial antagonists (such as *Bacillus pumilus* (M1), *Pseudomonas fluorescens* Biotype F (DF37)) and plant extracts (*Astragalus canadensis* L) have been found effective in controlling Verticillium wilt (Uppal *et al.*, 2007).

Bacterial wilt (*Ralstonia solanacearum*):

The pathogen has host plants such as chili, tomato, tobacco, and eggplant, as well as several other species of weeds that are commonly found in farmer fields. Management of this disease using available agrochemicals is difficult because of the soil-borne nature of *Ralstonia solanacearum*. However, farmers should be encouraged to use disease-free planting materials. Proper selection and use of fields that are free from bacterial wilt pathogen have been recommended for the management (Muthoni *et al.*, 2012). During rotation, cabbage/cauliflower should come immediately before potato due to their capacity to significantly reduce *Ralstonia solanacearum* (Larkin *et al.*, 2011).

Viral disease (Leaf roll virus, Potato virus Y, Potato Mosaic virus):

The common viral diseases include Leaf roll virus, Potato virus Y, and Potato Mosaic virus. These diseases could be managed through proper selection of disease-free fields and planting of disease-free and certified seeds from tolerant varieties. Management of vectors, such as whiteflies, aphids, and thrips should be done as explained under potato pests section.

9. HARVESTING AND POSTHARVEST OPERATIONS

Potato harvesting involves two key processes viz.: digging out of whole plant and collection of tubers by plucking/picking from the mother plants. Postharvest operations entail any treatment, processing, and storage of harvested potatoes. The timing of harvesting depends on the purpose of the crop (seed production versus market processing); maturity period of the variety used- early maturing (<85 days), medium maturing (85-100 days) and late maturing (>100 days); and prevailing weather conditions- extended rains when the tubers have matured and ready would force early harvesting to reduce losses caused by pest and disease attacks, sprouting and rotting of tuners. Generally, the maturity periods for most of the varieties grown vary between 70 and 120 days after planting. The signs of physiological maturity involve the shedding of leaves (drying off process) and tuber skins hardening and do not slip off easily. The harvesting period should coincide with dry weather, low water, and high temperature, to minimize handling and curing process before storage.

9. 1. Pre-harvesting practices

- **Water control:** By stopping irrigation 2-3 weeks before harvesting to fasten tuber skin setting and hardening. This is carried out when production is through irrigation or as a supplement to low rainfall.
- **Carrying out Dehaulming:** Dehaulming is the process of killing the above ground potato stems by either using chemical (e.g. Gramoxone herbicide or propane gas) or mechanical method (e.g. stumbling or beating with a rod or machine or cutting with a sickle) at physiological maturity stage. According to [31] Kenya Agricultural & Livestock Research Organization, This practice should be done 2 weeks before harvesting. This process should be slow to reduce chances of vascular ring discoloration, which is likely to affect tuber quality. Some of the reasons for dehaulming include;
- To harden the tubers and allow for a faster and stronger skin set that reduces bruising and skimming during harvesting and transportation.
- To stop the spread of diseases (e.g. late blight, stem rot, and bacterial wilt and viral diseases) from stems to tubers.
- For ease of harvesting process since the field is clear.
- To control tuber sizes especially under early dehaulming and shortens dormancy period in seed tubers.
- **Haulm/stover collection from the field:** This is done by raking the cut vegetative parts that are then burnt or thoroughly decomposed to reduce the spread of disease (like Late blight) and clear fields for harvesting.
- **Light irrigation** is sometimes done about 24 hours to harvesting on hard soils to reduce mechanical damage of tubers during harvesting.

10. CONCLUSIONS

The stagnated potato yields realized in the region is due to poor agronomic practices applied by farmers despite available technologies for adoption. Across the production chain, high seed recycling greatly contributes to the low yields realized. Farmers should be advised to always purchase fresh seeds every season from certified dealers for production. Weed control should be timed at 30 and 50 days after emergence for better yields. Fertilizer application is an important practice and should be done within the economic optimum levels. The N, P and K nutrients should be applied at levels not more the 150, 45 and 150 kg per hectare across East Africa unless soil analysis report has shown the need for higher rates. Calcium (Ca) and Magnesium (Mg) are also among the most important secondary nutrients required potato production. These nutrients should be supplied at rates of about 13 kg/ha each in case of deficiencies.

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