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Understanding tropical maize (*Zea mays* L.): The major monocot in modernization and sustainability of agriculture in sub-Saharan Africa

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ABSTRACT

Maize is the second most important cereal crop in the world after wheat followed by rice. Although, it is among the latest entries in the list of food crops in Africa, maize has attracted much more attention in terms of research and adaptability. Consequently, maize has become the number 1 crop with significant contribution to modern farming and food security in sub-Saharan Africa (SSA). Majority of the population in the region depend on maize as their main source of calories, income and livelihood. Additionally, maize is of global importance as a model organism for advancement of genetic studies. However, maize production in the region is conditioned by complex factors leading to very low average yield compared to other parts of the world. General understanding of tropical maize is one of the key approaches required for improvement of tropical maize in SSA. Here an attempt was made to review various aspects of maize and major advances including the origin, taxonomy, genetics, morphology, physiology, cultural practices, yield potentials, breeding, and production constraints. The information generated could provide useful insights into tropical maize and might contribute towards enhancement of the crop for food security in SSA.

INTRODUCTION

Maize (*Zea mays* L., 2n=2x=20, family Poaceae) is the most important cereal crop after wheat followed by rice in the world and is the first in Sub-Saharan Africa (SSA) where over 80% of the population depends on it as sources of food, income and livelihood (Pardey et al., 2016; ASARECA, 2014; Ranum et al., 2014; Sharma and Misra, 2011). About 25 × 10^6 ha of cultivated land in SSA is being utilized for maize production (Isabirye and Rwomushana, 2016; Smale et al., 2011). Maize plays a central role in SSA for example, in South Sudan maize is directly used by millions of people as food, drinks, animal feeds, cooking energy and construction materials (FAO/WFP, 2016). Lesotho is the leading consumer of maize in SSA with annual per capita consumption of 117 kg, followed by east Africa region with an average per capita consumption of about 100 kg per year (ASARECA, 2014). Elsewhere, maize is processed into different products

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Figure 1. Hybridization between teosinte and maize (adapted from https://learn.genetics.utah.edu/content/selection/corn).

such as starch, corn syrup, sweeteners, oil, beverages, glue, alcohol and fuel ethanol which are important for industrial purposes as well as animal feed (Ranum et al., 2014). More importantly, maize has become a model crop for molecular studies which has led to successful breeding and wider adaptation in Africa (Haberer et al., 2005; Jiao et al., 2017; Vivek et al., 2010). As a result, maize is considered a major crop in modern farming transformation and elevation of food security in SSA (Figure 1).

Despite the great importance of maize in agriculture and the enormous research investigations being undertaken, maize production in the region remains below the average global yield due to complex biotic and abiotic constraints. Holistic understanding of tropical maize is one of the key approaches required for improvement of maize production in SSA. Here we attempted to review various aspects of maize and major advances including the origin, taxonomy, genetics, morphology, physiology, cultural practices, yield potentials, breeding, and production constraints. The information generated might provide better insights into tropical maize and might contribute towards enhancement of the crop for food security in Sub-Saharan Africa.

ORIGIN OF MAIZE

The word '*maize*' is definitely believed to have been deformed from the original name '*mahiz*' in Sarawak-Caribbean language (Ortega et al., 1980). Maize crop is believed to have originated from wild grasses called teosintes some 10,000 years ago in the Meso America region (today known as Mexico, Guatemala and Honduras) (Figure 2) (Doebley, 2004; Eichten et al., 2011; Schnable, 2015). Because of low rate of gene flow (intercross), maize and teosinte are still co-existing as separate entities (AGOGTR, 2008). Maize is also related to sorghum (*Sorghum bicolor* L.) in terms of genome assembly. The two crops are assumed to have separated from each other just about 12 million years ago (Schnable, 2015).

Maize is believed to have been domesticated as source of food about 6000 years ago. The crop was first introduced to the Americas following discovery of the continent by European travelers during the 15th century, later, it spread to Sub-Saharan Africa and rest of the world (Fonseca et al., 2015; AGOGTR, 2008). Over time, each region has maintained specific maize cultivars adapted to its conditions.

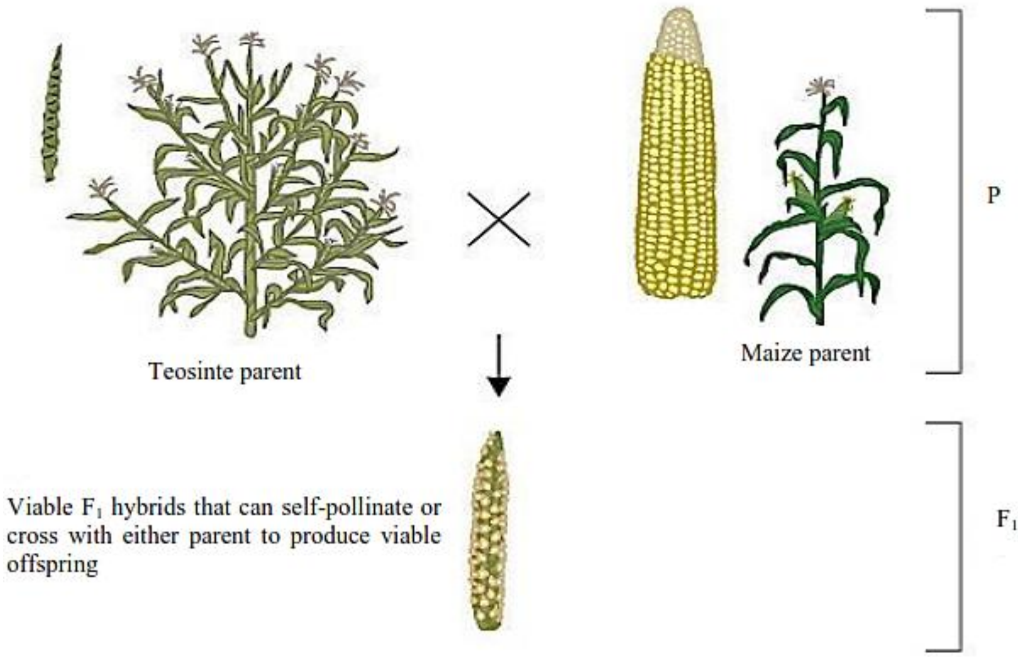

Figure 2. Hybrid crosses between teosinte and maize parents.

Table 1. Taxonomic classification of cultivated maize.

Taxonomy	Classification
Kingdom	Plantae
Subkingdom	Tracheobionta (Vascular plant)
Supper-division	Spermatophyta (Seed plant)
Division	Magnoliophyta (Flowering plant)
Class	Liliopsida (Monocotyledon)
Subclass	Commelinidae
Order	Cyperales
Tribe	Andropogoneae
Family	Poaceae (Grass family)
Subfamily	Panicoideae
Genus	Zea
Species	*Zea mays*
Subspecies	*mays*

TAXONOMY OF MAIZE

The cultivated maize, also called '*corn*' in some parts of the world, belongs to the genus *Zea* from the tribe of Andropogoneae in the family of Poaceae, subfamily Panicoideae (Table 1). There are six other wild species of maize that belong to the same genus but they are wild grasses (called teosintes) and not being used for cultivation. The six species of maize, except *Zea perennis* (Perennial teosinte with $2n=2x=40$), have similar chromosome number of $2n=2x=20$) (Table 2).

MAIZE GENOME

In addition to being a crop of major economic importance, maize is a model organism for studies in plant genetics, physiology and crop development. It is a diploid crop with 10 pairs of chromosomes and each chromosome contains 2 alleles ($2n=2x=20$). Maize genome, first

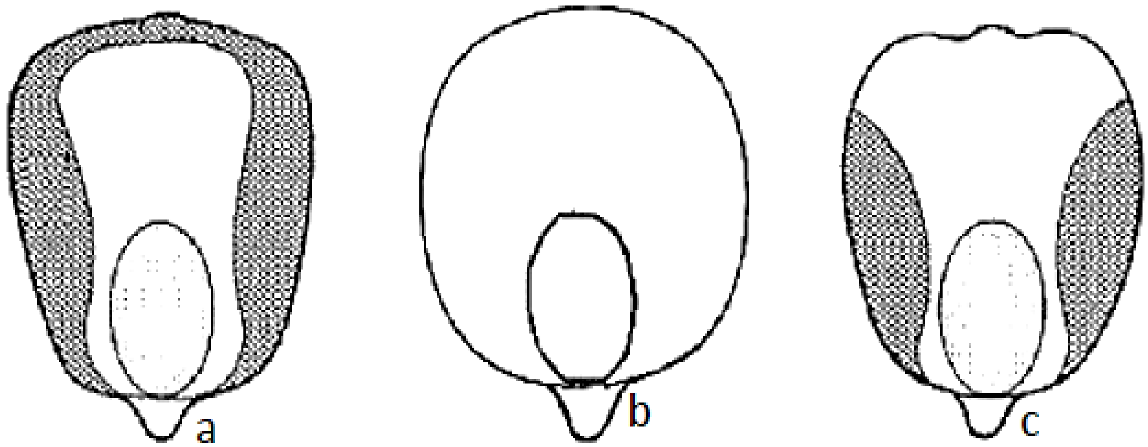

Figure 3. Typical Illustrations of common types of maize kernel: (a) Floury kernel maize is also grown for processing into flour due to its soft kernel and ease of milling however; it is not as sweet as dent types; (b) Flint kernel has hard endosperm with thiny soft centre; (c) Dent kernel maize with high content of soft starch.

Table 2. List of seven species of genus *Zea* and their chromosome numbers.

Species of maize	Chromosome number	Remarks
Zea mays L.	2n=2x=20	Domesticated and used by mankind
Zea parviglumis	2n=2x=20	Annual wild grass
Zea mexicana	2n=2x=20	Annual wild grass
Zea nicaraguensis	2n=2x=20	Annual wild grass
Zea luxurians	2n=2x=20	Annual wild grass
Zea diploperennis	2n=2x=20	Perennial wild grass
Zea perennis	2n=2x=40	Perennial wild grass

reported in 2009, is extremely large compared to some plant genomes (Michael and Jackson, 2013; Schnable et al., 2009). Previous reports show that maize has a genome size of 2.4 to 2.7 gigabase pairs (Gbp) with a total number of genes ranging from 42000 to 110000 (AGOGTR, 2008; Schnable, 2015; Schnable et al., 2009). More information on maize genome sequencing is available (http://www.maizegenome; http://maizesequence.org). Genomic sequencing allows identification of abnormal chromosomal arrangements such as repeated nucleotide sequences, transposons and retrotransposon elements. Some of these segments are associated with quantitative trait loci (QTL) which are commonly used for genetic improvement of maize for traits of economic importance (Gowda et al., 2018; Rasheed et al., 2016; Zhao et al., 2017).

TYPES OF MAIZE KERNEL

Cultivated maize has different types depending on shape of the kernel (grain) and composition of the endosperm (Figure 3). The most common kernel types include flint, dent, floury and waxy kernels. Elsewhere, pop and sweet corns are also common (AGOGTR, 2008; Brown et al., 1985).

USES OF MAIZE

Maize plays a central role in SSA where it is directly used by majority of the population as food, drinks, animal feeds, cooking energy and construction materials. Lesotho is the leading consumer of maize in SSA with annual per capita consumption of 117 kg, followed by east Africa region with an average per capita consumption of about 100 kg per year (ASARECA, 2014). Elsewhere, maize is processed into different products such as starch, corn syrup, sweeteners, oil, beverages, glue, alcohol and fuel ethanol which are important for industrial purposes as well as animal feed (Ranum et al., 2014). More importantly, maize has

Figure 4. Diagrams showing some common global uses of maize: (a) Ornamental; (b) food, feed and industries; (c) bio-fuel and ethanol; (d) young maize silk used as herbal medicines.

become a model crop for molecular studies which has led to successful breeding and wider adaptation in Africa (Haberer et al., 2005; Jiao et al., 2017; Vivek et al., 2010).

Maize is an important crop with significant contribution to global economy especially in the developed world where it is considered as industrial material (Figure 4) (Espinoza and Ross, 2010; Ranum et al., 2014; VIB, 2017). With the effects of climate change due to huge volumes of carbon dioxide being released annually into the atmosphere, the world is hoping to maximize usage of bio-fuel other than inorganic energy. In this perspective, maize has become a major cereal in the last few years in the bio-fuel industry (Ramirez-cabral et al., 2017; Belfield and Brown, 2008; Ranum et al., 2014). For example, in the USA, about 40% of mize production goes into production of ethanol every year. Due to moderate cost of production and high dependent on maize as source of food in developing countries, and where micronutrient deficiencies are common public health issues, maize is also becoming an ideal crop for food bio-fortification such as enhancement of pro-vitamin A (Ranum et al., 2014; Espinoza and Ross, 2010).

MORPHOLOGICAL CHARACTERISTICS OF MAIZE

Maize is an advanced higher organism with well-developed morphological structures and each structure performs distinct and specialized biological and physiological functions. This has permitted maize to be considered as a model organism for conducting scientific investigations.

MAIZE SEEDLING

Soon after germination, a seedling is developed which consists of mesocotyl (shoot) and radicle (root) emerging from the caryopsis (fruit) (Figure 5). The shoot apex, sheathed by the coleoptile, is pushed through the soil by the elongating mesocotyl and unexpanded leaves (Bousselot et al., 2017; Espinoza and Ross, 2010; Markelz et al., 2003). Maize seedling has rudimentary root and shoot systems therefore, it mainly depends on reserved food found in the caryopsis below the ground for its nutrients. As the leaves emerge and roots expand, the seedling begins to capture more sunlight and synthesizes its own food (photosynthesis).

MAIZE PLANT

Maize is a tall, determinate annual plant belonging to monocotyledon class and is monoecious with separate male and female flowering organs but on the same plant (Figure 6). Shanks develop in the leaf axis and will mature into female inflorescence (an ear). Depending on the variety, more than one shanks may develop on one maize plant but usually only 1-2 may develop into economic ears (cobs). Ears are covered by a number of leaves (husks) and each cob has even number of rows (8-30) of kernels (du Plessiss, 2003; Iltis, 2000). Each ovary contains one ovule which will mature into a kernel. One ear of maize contains between 300-1000 kernels (AGOGTR, 2008). The apical meristem of maize stalk develops into a tassel which consists of central spike and up to 40 lateral branches carrying male flowers. The tassel structure is erected on top of the plant by a strong peduncle. Maize stem has protective epidermis that covers layers of sclerenchyma tissues resulting into strong stalk. Generally, tropical/sub-tropical varieties are taller unlike their temperate counterparts (AGOGTR, 2008).

ROOT SYSTEM

Maize roots are very shallow due to their adventitious nature where no tap root is observed. Normal maize plant can develop 4-6 adventitious roots of almost equal sizes (Figure 7). The adventitious roots develop from nodes below the soil surface. Root length can reach 1.5 m laterally and about 2.0 m deep (Espinoza and Ross,

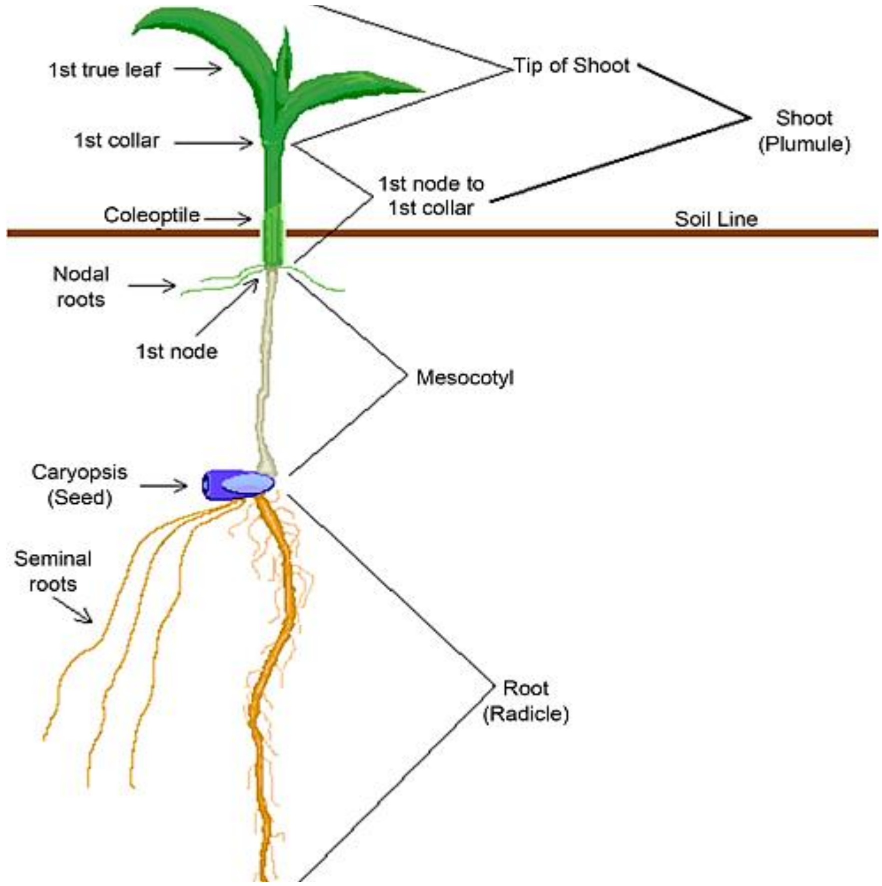

Figure 5. A diagram showing morphology of a maize seedling (Bousselot et al. 2017).

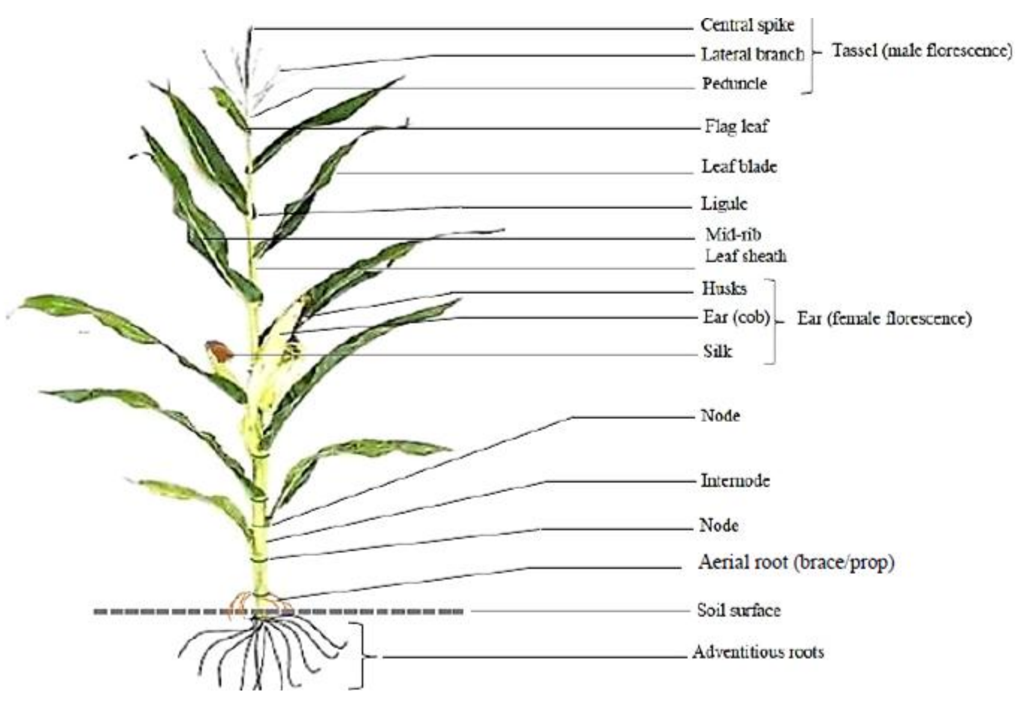

Figure 6. A diagram showing typical morphology of a mature maize plant with different parts.

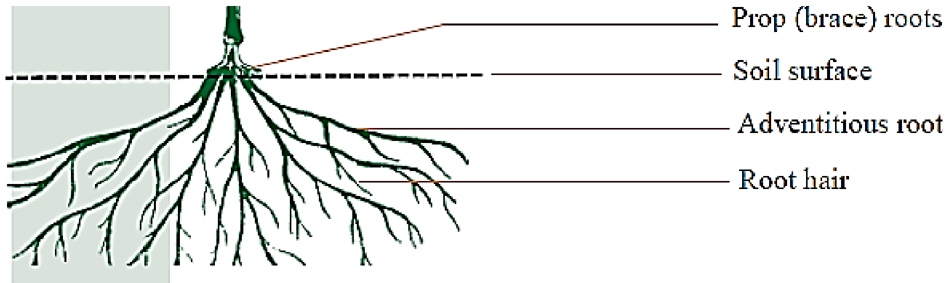

Figure 7. A diagram representing maize root system with complete prop roots, adventitious roots and root hairs (du Plessis 2003).

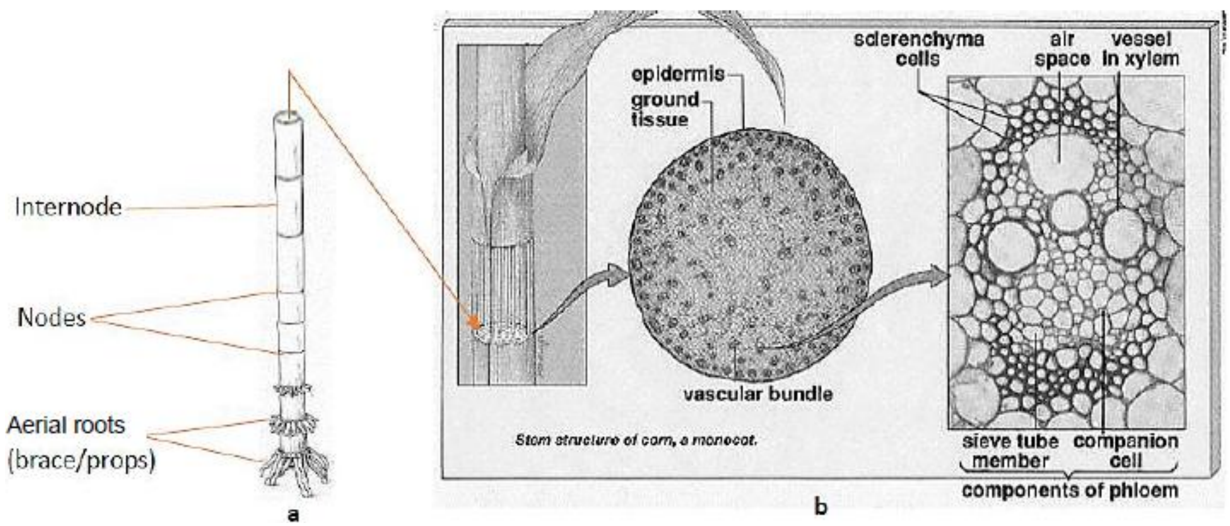

Figure 8. Morphological and physiological illustrations of maize stem: (a) morphology of maize stem showing nodes and internodes; (b) cross section of miaize stem showing vascular bundle and the sclerenchyma cells (adapted from: http://mandevillehigh.stpsb.org).

2010; Belfield and Brown, 2008; du Plessiss, 2003). The roots are instrumental for absorption of water and nutrients from the soil.

STEM

Depending on the variety and environmental conditions under which the plant is grown, normal maize plant has a single stem of about 0.5-5 m tall (measured from the soil surface to the point where flag leaf is attached to the peduncle). The stem is cylindrical, solid and divided into nodes separated by internodes (Figure 8). Internodes are cylindrical in the upper part, and alternately grooved on the lower part of the stem with a bud in each groove, with one or occasionally two lateral branches in the leaf axils in the upper part of the plant. Grooves are required for proper positioning of the ears.

LEAF

Leaves are the photosynthetic organs responsible for food production. The upper leaves are more responsible for light interception and are major contributors of photosynthate for grain filling. About 8-30 leaves may form on one plant and are arranged spirally on the stem (Figure 9). Stomata occur in rows along the entire leaf surface and more are found on the underside of the leaf than on the upper surface (Zarinkamar, 2006). During moist conditions, cells rapidly absorb water, become turgid and unfold the leaf. However, under warm, dry weather conditions, the cells quickly lose their turgor and as a result, the leaves curl inwards hence water loss due

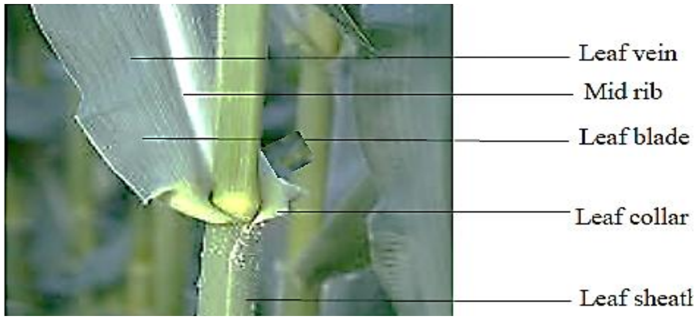

Figure 9. A diagram showing morphology of mature maize leaf. Maize leaf consists of a sheath, leaf collar (ligule) and leaf blade.

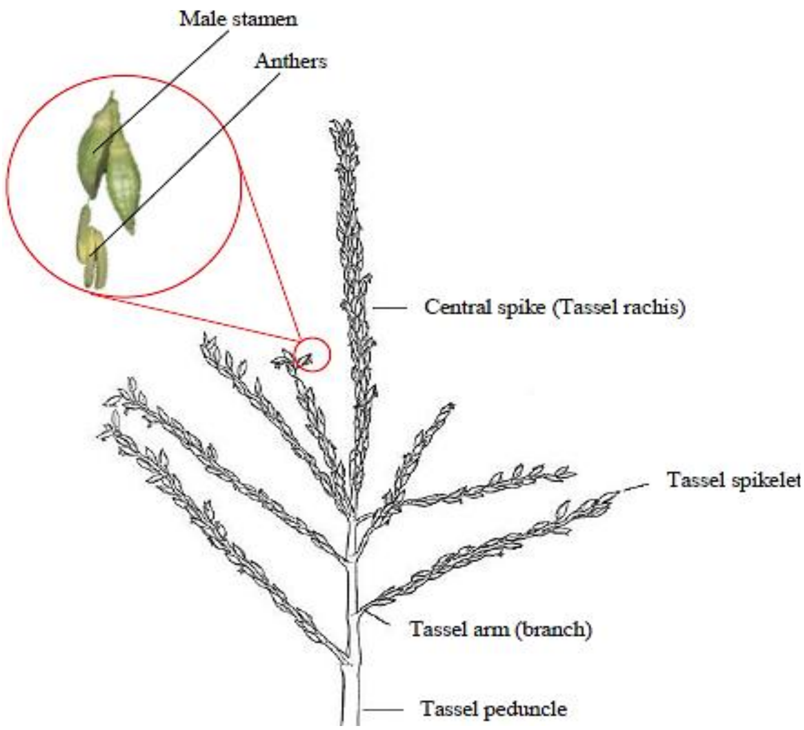

Figure 10. Maize male flower (tassel) showing different parts including mature stamen and anthers.

to evaporation is minimized since smaller leaf surface is exposed to the air (du Plessiss, 2003).

FLOWER

Maize is a typical monoecious plant, that is, it produces two morphologically incomplete (male and female) flowers. The male flower only contains stamen while the female flower has pistil. Though the two reproductive organs are on the same plant, they are situated on different parts of the plant.

Male flower (tassel): Male flower is called tassel and is borne on the top of a maize plant, supported by a peduncle. Tassel is developed from the apical meristem of maize stalk (AGOGTR, 2008). Normally, one maize plant carries only one tassel made up of central spike (tassel rachis) and about 20-50 tassel arms (branches). Each arm carries several male stamens and each male stamen contains 3 anthers dangling out on slender filament (Figure 10). Anthers are the male organs

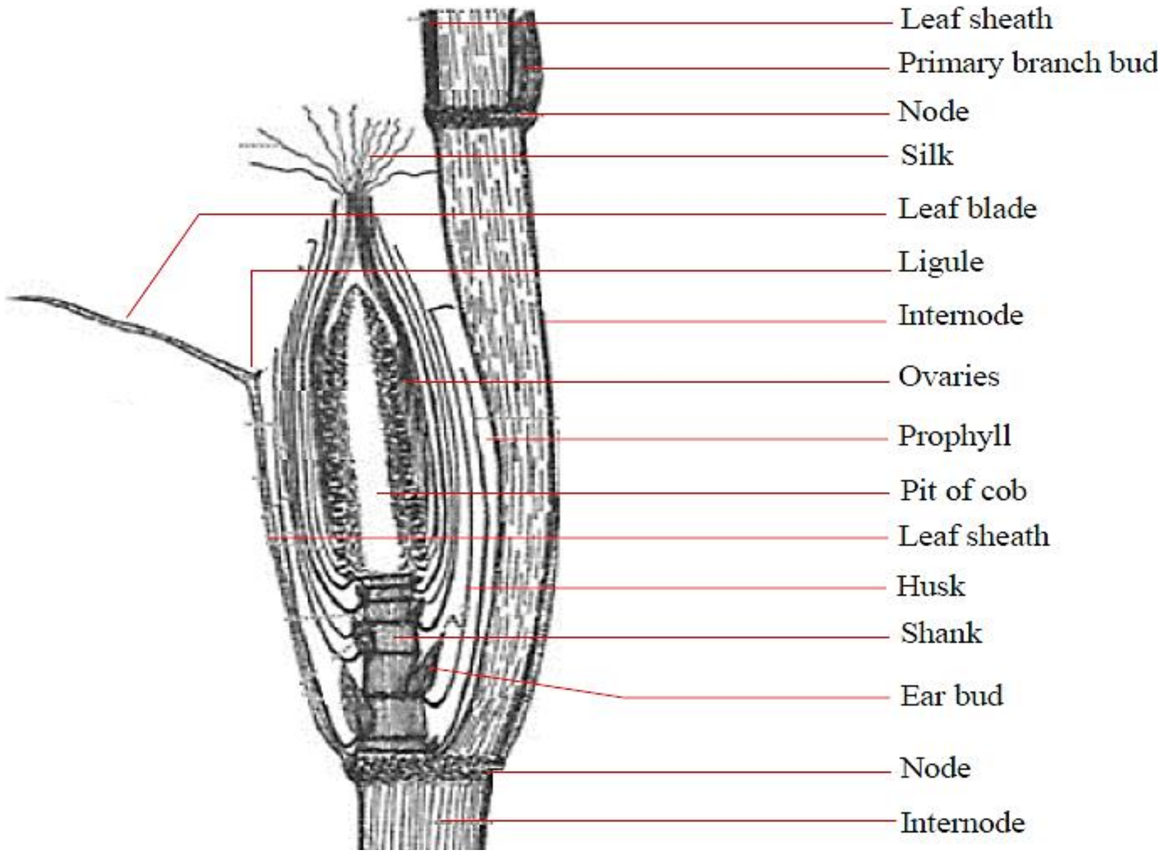

Figure 11. A cross-sectional illustration showing a maize ear and its silks (Iltis, 2000).

responsible for production and dispersal of millions of pollen into the air (VIB, 2017; Hofmann et al., 2016).

Female flower (ear): Ear is the female reproductive part of maize and it grows from the shanks (stalk-like structures) that are developed from axillary bud towards the middle of the stem length. Lateral shoot carrying the main ear emerges from the groove in the 8th node above the soil surface. One or two nodes below the 8th bud may produce rudimentary lateral shoots where one or two of them may develop into mature ears (AGOGTR, 2008; du Plessiss, 2003). Sometimes, maize plant may initiate many ears up to 12th or 14th node but normally the upper most will grow to a full ear (Figure 11). Ear contains cob (rachis) with rows of sessile bearing spikelets, that eventually grow into kernels and silks (Iltis, 2000). First, silks at the base of the cob emerge followed by those towards the tip. Silks can remain viable for up to 10 to 14 days so as to allow ample time for pollination. Excessive heat, moisture and senescence can affect silking. Silks are attached to ovaries arranged in rows (8-30) found on a cob, and covered in leaves (husks). Each ovary contains one ovule which matures into a kernel. Typically, an ear contains up to 1000 ovules and all silks must be pollinated so that the 1000 ovules mature into kernels. However, due to missing pollination, number of mature kernels per cob may be low (AGOGTR, 2008; Iltis, 2000). While row number is determined soon after ear initiation, ear length is confirmed towards tasselling. Both row number and ear length are affected by stresses starting at V5 stage.

FRUIT AND SEED

After the elapse of fertilization, maize seed, which is a combination of both fruit and seed (also called kernel or grain), is formed. Seed contains approximately 72% starch, 10% protein, 4% fat and 1.4% ash, supplying an energy density of 365 Kcal/100 g (Ranum et al., 2014). In addition, maize seed contains vitamins A and E, as well as riboflavin and nicotinic acid (Table 3). It is a dry indehiscent single-seeded fruit (caryopsis) containing three main compartments: fruit wall (brand), endosperm and embryo (Figure 12).

Fruit wall: Is a structure tightly adhered to the fruit, is formed out of pericarp (ovary wall) and testa (seed coat)

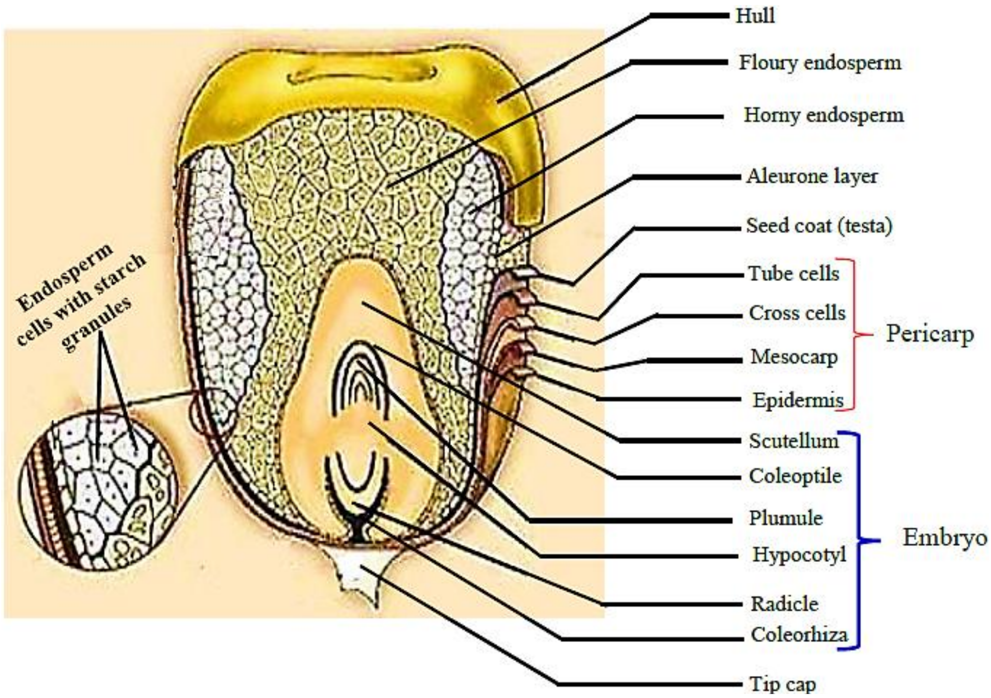

Figure 12. A cross-sectional view of a viable maize kernel (Adapted from Encyclopedia Britannica, Inc, 1996) (https://www.britannica.com/technology/cereal-processing#ref501165).

Table 3. Storage reserve compounds available per 100 grams of maize grain.

Compound	Energy
Energy	360 kJ (86 kcal)
Carbohydrates	18.7 g
Fats	1.35 g
Protein	3.27 g
Water	75.96 g
Zinc	0.46 mg
Phosphorus	89 mg
Potassium	270 gm
Vitamin A	NA
Vitamin C	6.8 mg
Vitamin E	NA
Iron	0.52 mg
Magnesium	37 mg
Ash	NA

which provides protection to the seed. Seed coat (testa) is the outer layer of the seed consisting of membranous structures that are fused with fruit wall (hull) to envelope the embryo and endosperm. Seed coat is responsible for internal protection against biotic stresses, mechanical injury and desiccation. It is also important for gas exchange, water uptake and control of nutrients for embryo and endosperm. The coat plays key roles in seed viability, longevity, dormancy and germinability (Sliwinska and Bewley, 2014). Pericarp is a protective cover develops from the ovary wall.

Endosperm: Is a thick component (80-85%) of grain, consisting of stored food reserves that is used by the seedling before the plant establishes its own photosynthetic structures (Ognakossan et al., 2018). Maize endosperm is separated from the outer aleurone and subaleurone layers by a radial symmetry which is composed of three sections: (i) embryo-surrounding region; (ii) the central (largest portion of the endosperm); and (iii) the basal endosperm transfer layer (Sliwinska and Bewley, 2014). Endosperm (tip) cap acts as a closer for radicle tip and prevents radicle emergence, and enhances seed dormancy. Size of endosperm varies among maize varieties depending on how much reserve food has been transferred to the endosperm during developmental stages.

Embryo: Embryo (germ) constitutes about 9-10% of seed volume and contains most of the nutrients in grain (33% fat, 19% proteins, minerals and vitamins B complex and E), and is rich in unsaturated fatty acids (oleic and linoleic acids) (Ognakossan et al., 2018). This is the germ of maize consisting of one embryonic axis (complex) with only one cotyledon (monocotyledon), situated in a groove at one end of the endosperm. Embryo is vital for seed germination. The embryonic axis composed of four parts: (1) the radicle; (2) hypocotyl; (3) epicotyl; and (4) plumule (shoot apex), with a transitional zone between the radicle and hypocotyl. The radicle is located close to micropyle and it contains root meristem which develops into embryonic root when germination is complete. Hypocotyl is a stem-like region of the embryonic axis terminated by radicle at the basal end and by cotyledon at the proximal end. Epicotyl is the first shoot segment above the cotyledons. In maize, cotyledons may be well developed and serve as storage organs for reserves, or remain thin and flattened (endospermic seeds). Scutellum is a large shield-shaped body formed as a result of shrinkage in cotyledon structure followed by elongation of the basal sheath of the cotyledon to form a coleoptile that covers the first leaves. Coleorhiza is a protective sheath enclosing embryonic root structure and it provides protection against damages.

REPRODUCTION SYSTEM IN MAIZE

Maize plant is a sexually reproducing organism with well-developed male and female reproductive systems. No report of asexual reproduction has been found in maize however, under advanced laboratory conditions, vegetative parts of maize such as embryos can be manipulated using tissue culture techniques to grow into a maize plant with complete morphology (Jones, 2009; Wang et al., 2012). Reproduction in maize involves various developmental stages.

GAMETE FORMATION

Both male and female reproductive organs contain mature sporophytes (Figure 13). During gamete development, male sporophyte (2n) undergoes meiosis cell division to produce microspore (n). The microspore further divides mitotically (male gametogenesis) to produce microgametophyte which contains 3 gametic cells (2 sperm cells and 1 vegetative nucleus) (Dumas and Mogensen, 1993). Similarly, female sporophyte (2n) divides through meiosis to generate megaspore (n) which then undergo three successive non-nuclear mitosis divisions (female gametogenesis) to produce megagametophyte with two cells: central cell containing 2 nuclei, and egg cell with 1 nucleus (Sliwinska and Bewley, 2014; AGOGTR, 2008).

POLLEN SHED AND DISPERSAL

As soon as the tassel is fully emerged, pollen shed (anthesis) begins and may continue up to 2 weeks. Normally, anthesis lasts for 5 to 8 days with peak of pollen shed on the third day. Ideal period for pollen shedding is morning hours because hot/dry weather and excessive humidity delay flowering and affect pollen viability (AGOGTR, 2008). Under normal cultural practices and favourable environmental conditions, huge amount of pollen (10^{10} to 10^{13} pollen grains/plant) can be produced. Total amount of pollen disposed in the same field is about 23.3 million pollen grains/m^2 (Hofmann et al., 2014). Pollen grain is dispersed by wind or animals (especially flower-sacking insects) and can be transported up to a distance of 300 meters from the point of disposition (AGOGTR, 2008). When deposition occurs at higher altitudes, pollen grains can travel as far as 3.3 to 4.45 km. Factors such as wind direction, field size, plant density, maize variety, growing conditions, agricultural management and weather conditions affect pollen disposition and dispersal (Hofmann et al., 2014). After disposition, pollen grain remains viable in the field for 1-4 h depending on the weather conditions. However, pollen can be stored for longer period under cold conditions such as in laboratory (Bannert, 2006; Bots and Mariani, 2005; Fonseca and Westgate, 2004).

POLLINATION AND FERTILIZATION

Pollination refers to the transfer of pollen grain from the anther to the silk. Fertilization is the process by which male gamete from the pollen unites with female gamete from the ovule to form a zygote. Fertilization can occur only when cell division is complete. First, pollen grain is carried onto the female reproductive organ (silk) by wind and animals (especially insects) or by direct physical contacts between the plants. Unlike other organisms, maize exhibits double-fertilization: embryo fertilization and endosperm fertilization (Faure et al., 2003; Dumas

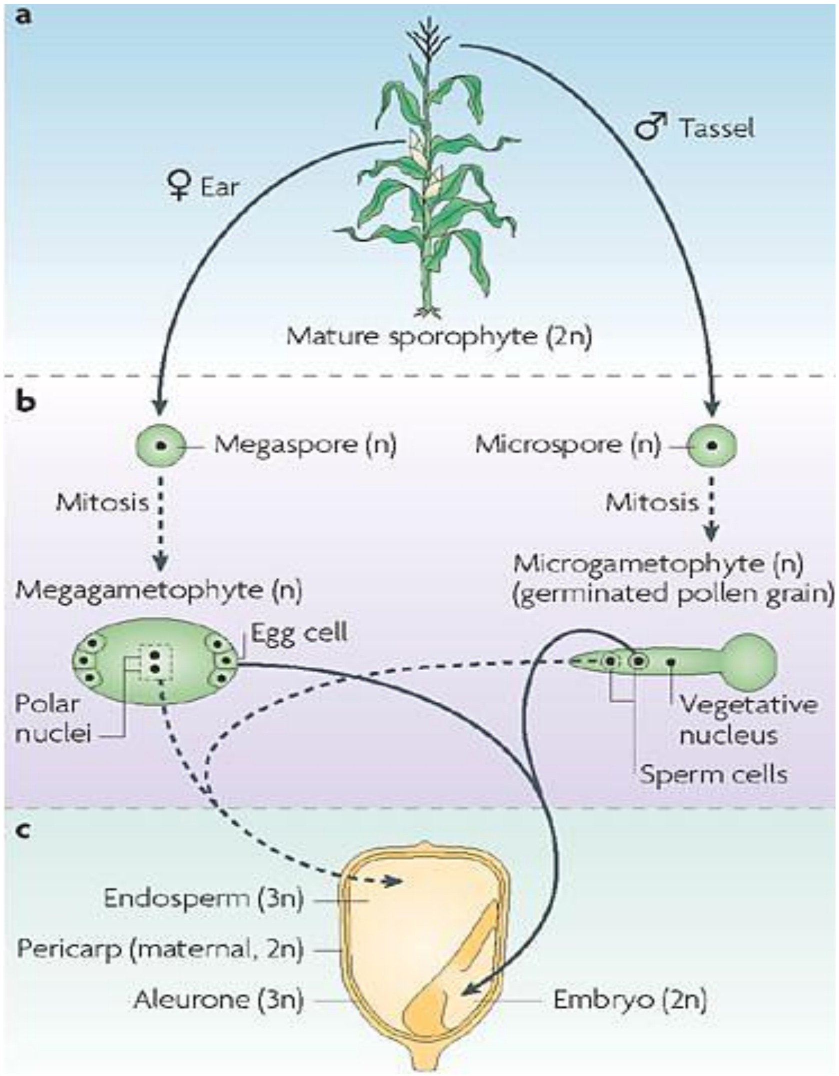

Figure 13. Schematic illustration of gamete development and the mechanisms of double-fertilization in maize: (a) Mature sporophytes (2n) from each of male (tassel) and female (ear); (b) meiosis cell division stage for production of germ cells (n); and (c) double-fertilization stage where both embryo (embryogenesis) and endosperm are formed (Nature Reviews Genetics: www.nature.com).

and Mogensen, 1993). One of the 2 sperm cells fertilizes egg cell to form an embryo with 2n (embryo fertilization) while the remaining sperm cell fuses with central cell nuclei to form an endosperm with 3n (endosperm fertilization) (Figure 14). The question of which of the two male gametes to fuse with which female cells (non-random fertilization) has been discussed in detail elsewhere (Faure et al., 2003). Fertilization occurs 12-28 h after pollination. During pollination and fertilization period, enough water and nutrients are required and therefore, supplementary use of irrigation and application of fertilizers are needed. Maize is an out-crossing crop thus, only 5% of kernels may be fertilized with pollen from the same plant. The silk can remain receptive up to 10 days after emergence however, silk begins to die off 7-8 days after emergence depending on the environmental conditions (Bannert, 2006).

EMBRYOGENESIS

Embryogenesis is the process in which a fertilized egg cell (zygote) develops into a mature embryo. First phase of embryogenesis occurs within 100 h after fertilization in which a proembryo structure with 12-24 cells is produced. The basal cell divides into large vacuolated cells while

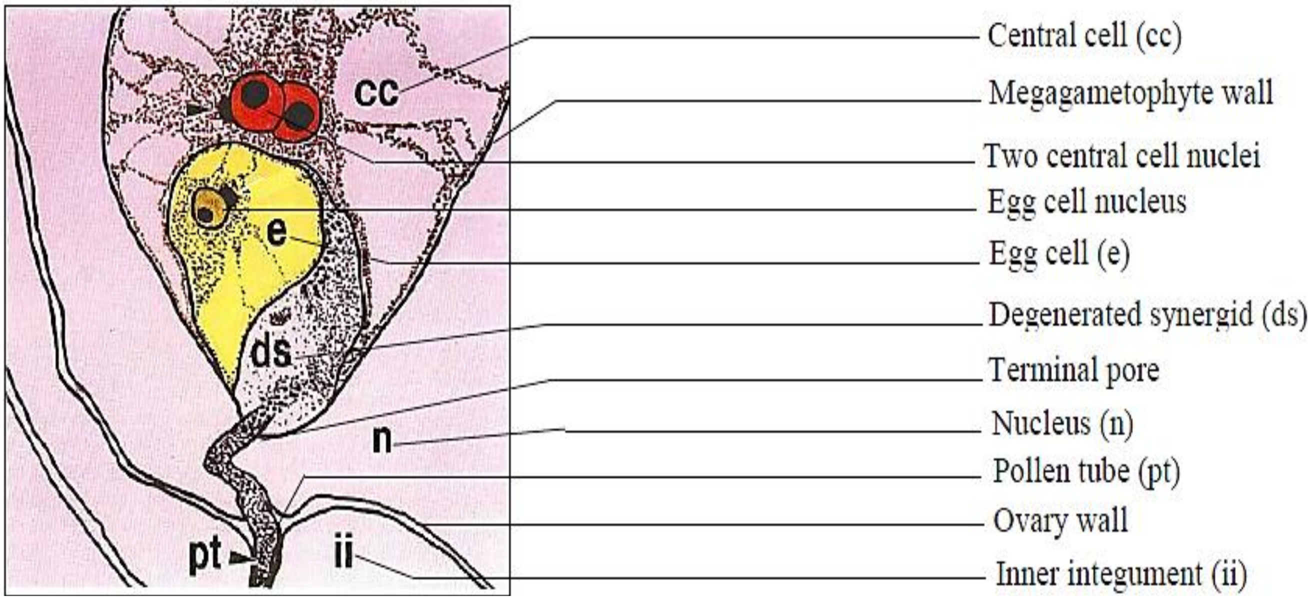

Figure 14. Schematic illustration of double-fertilization (embryo fertilization and endosperm fertilization) processes (Dumas and Mogensen, 1993).

the apical cell divides to generate 9-18 smaller cells (AGOGTR, 2008). Second phase of embryogenesis begins 8-9 days after fertilization, followed by formation of meristem and embryogenic axis at 13 days from the day of fertilization (Fong et al., 1983). This stage is followed by formation of a coleoptile-like structure within 14-15 days after fertilization, which then differentiates to form scutellum, coleoptile, coleorhiza as well as root and shoot apical meristems. First leaf primordium emerges 16 days after fertilization resulting to stage 1 embryo of about 1 mm long. This is followed by more leaf primordia and primary and secondary root primordia development, leading to complete embryo formation covered by scutellum about 30-40 days after first leaf primordium (AGOGTR, 2008).

XENIA EFFECTS

Maize is a monoecious (separate male and female flowers on the same plant) and cross-pollinated plant, making it ideal for xenia occurrence. Xenia refers to the situation where pollen from different maize plant falls on the silks of another maize plant and causes fertilization (Castaneda, 2010; Poehlman, 1987). It is a serious issue affecting grain quality and production. Grains developed due to xenia fertilization show different morphological appearances because of difference in sources of pollen. A typical example of xenia effect is where grains on same cob exhibit different colours and textures (Figure 15) (Poehlman, 1987; Brown et al., 1985).

SEED DISPERSAL

Maize structure does not allow seed to naturally disperse. Mature maize grain dries on the cob, making it difficult to move away. Dry maize plant usually falls down together with the cob containing the seeds (especially when harvest is over delayed). As a result, seed usually germinates at the same spot provided favourable conditions prevail (AGOGTR, 2008). However, forced seed dispersal can occur in maize through the aid of animals and man, whereby maize grain can be transported over long distances or even across continents.

SEED DORMANCY

Seed dormancy refers to genetic characteristics of plant that allow manipulation of environmental conditions so as to prevent seed germination within a given period. Seed dormancy normally occurs in maize grain due to accumulation of carotenoid and abscisic acid (ABA) which are important compounds for prevention of preharvest sprouting (vivipary growth) and germination. For example, if maize seed is treated with fluridone (a pyridinone compound) 1-2 weeks after pollination, ABA accumulation and carotenoid biosynthesis are disrupted, leading to vivipary induction during maize seed development (Fong et al., 1983). At dormancy, maize seed is alive but is in a quiescence state in which metabolic respiration rate, seed water content and

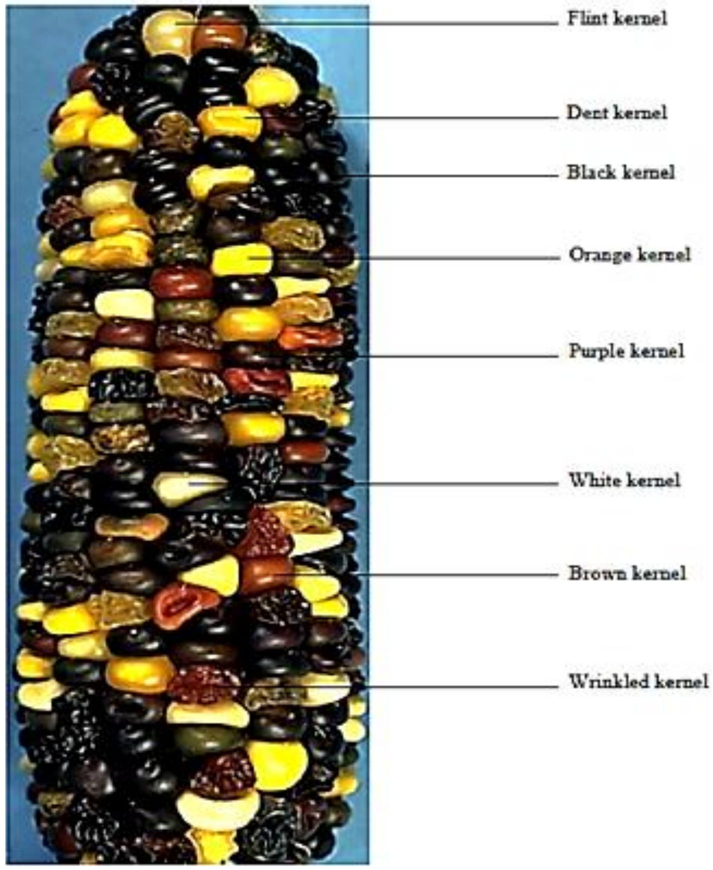

Figure 15. A diagram of maize ear showing kernels with different xenia effects.

synthetic activities (for example, RNA synthesis) are very low (Walle and Bernier, 1976). Seed respiration can be minimized by keeping the seed under cool and drier conditions. This allows seed to be stored for many years without reducing the viability (Kansas State University, 2007).

GERMINATION

Germination is the physiological process during seed transition from a dormant state to a vital active state. Seed germination requires favourable environmental conditions to allow changes of chemical and biological factors within the seed prior to initiation of germination (Rajjou et al., 2012). Germination occurs when the substrate moisture is 30% or higher, where the seed first imbibes water depending on seed-substrate contact during planting. Maize seed imbibes 1.5 to 2 times it dry weigh for germination to take place (Belfield and Brown, 2008). Minimum and maximum temperatures for maize seed germination are 10 and 30°C respectively. Variation in soil temperature affects days to germination. For example, at 10°C the seed takes 25 days to germinate; at 13-16°C the seed takes 10-14 days to germinate; and at 18-21°C the seed needs only 5-8 days to germinate (Kansas State University, 2007). Oxygen supply is very important during germination because the seed requires enough oxygen for respiration. Water-logged soil causes seed suffocation and seed death since oxygen is blocked. Maize seed germination is hypogeal (the energy storage part of the seed remains below the ground) where the plumule, covered in a protective coleoptile, is pushed through the soil to the surface (Espinoza and Ross, 2010). Sowing depth of more than 8 cm may delay seed germination. If seed is planted in drier soil with higher temperature, the seed may die if no moisture is availed (Belfield and Brown, 2008).

VEGETATIVE AND REPRODUCTIVE STAGES OF MAIZE GROWTH AND DEVELOPMENT

Maize is a sexually reproducing plant belonging to the

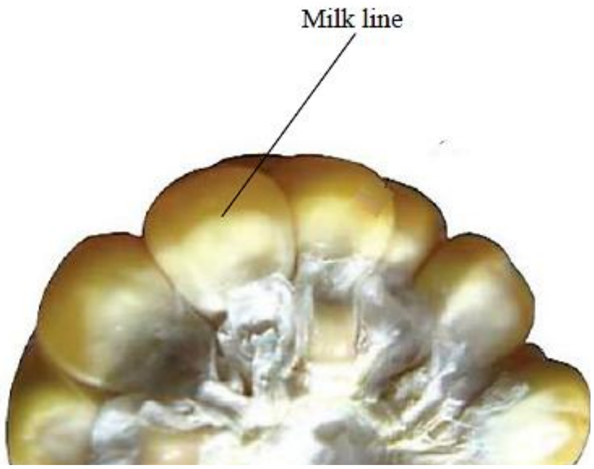

Figure 16. Cross section of maize cob indicating kernels with milk line separating soft and hard sections of a developing maize kernel (Belfield and Brown, 2008).

group of angiosperms therefore, its growth and development go through two physiological stages of vegetation and reproduction as the plant develops from germination to physiological maturity (Figure 16).

VEGETATIVE STAGES

Vegetative stages begin from seedling emergence and continue up to tasselling stage and are designated as VE, V1, V2, V3, …Vn, and VT; where *VE*=emergence stage, *V1*= first leaf stage (when plant develops first leaf with collar), *V2*= second leaf stage, *V3*= third leaf stage, …..*Vn*= n^{th} leaf stage, and *VT*= tasselling stage (Espinoza and Ross, 2010; AGOGTR, 2008; Belfield and Brown, 2008; Nafziger, 2008).

Emergence and establishment stages (VE to V2): When seed gets into contact with moist soil it absorbs enough moisture followed by emergence of root radical and mesocotyl from the seed coat where the mesocotyl grows towards soil surface. Exposure of coleoptile to sunlight leads to emergence of first leaf within 4-5 days from planting. The seedling will depend on food reserves from the caryopsis below the ground until it reaches 2-leaf stage (V2). Primary root then develops which absorbs water and nutrients from the soil and used by the leaves for initiation of photosynthesis.

Early vegetative stages (V3 to V10): This developmental stage (also referred to as knee-high stage) covers the period from post-emergence to floral initiation which takes about 3 to 4 weeks. At 10 days from seedling emergence (V3 to V4), adventitious roots are developed and involved in major roots functions. For the first 2 to 3 weeks, all leaves are emerging from a single growing point below the soil surface (Belfield and Brown, 2008). At about 3 weeks after seedling emergence, the growing point appears on the soil surface and an embryonic tassel is formed (V5), followed by initiation of ear formation. Leaf formation is fastest at this stage and at 4 weeks, 8 leaves are fully developed (V8). At this stage, nitrogen (N) fertilizer should be added as top dressing.

Late vegetative stages (V11 to V16): These are the last stages for vegetative growth in maize and considered the most critical stages because the plant grows very fast with high demand for water and nutrients especially nitrogen (N). Leaf emergence is complete at 5 weeks (V12) and root system is well established, covering almost the entire root zone. At weeks 5 to 7 (V11 to V16), all leaves are emerged with the highest 1 or 2 ears quickly developing and ear size is determined (Espinoza and Ross, 2010; Belfield and Brown, 2008). This is followed by determination of number of rows per ear and then number of kernels per row. Maize tassel reaches full size at 7 weeks from the date of sowing (V16). Maize plant is very sensitive at this stage and therefore, proper management is required such as optimum moisture, nutrient availability, weeding, diseases and pests control, etc. (Acquaah, 2012; De Groote, 2002; The Maize Program, 1999).

REPRODUCTIVE STAGES

Reproductive stages start during or immediately after

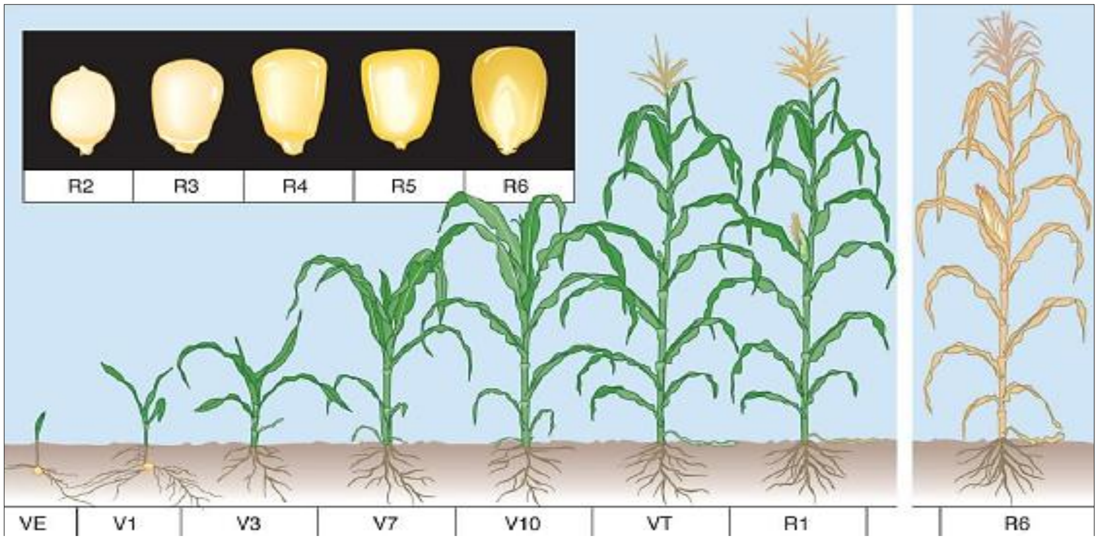

Figure 17. Schematic illustrations of different vegetative and reproductive stages of maize growth and development (Nafziger, 2008).

tasselling and are indicated as R1, R2, R2, R3, R4, R5 and R6; where *R1*= silking stage, *R2*= blister stage, *R3*= milk stage, *R4*= dough stage, *R5*= dent stage and *R6*= physiological maturity respectively (Espinoza and Ross, 2010).

Silking stage (R1): Maize tassel appears at the apex of the plant at 14 to 15 leaves stage, followed by pollen shed 40 to 50 days after seedling emergence, depending on the variety and environmental conditions. Silking stage (cob initiation stage) is where ear emerges in the axil of 11^{th} to 13^{th} leaf. Silking is more on the upper most ears though the lower ear may also produces silk depending on the maize variety. Pollination and fertilization of the ear occur at this stage. Maize plant is very sensitive to drought during flowering thus, there is high demand for water as well as fertilizers inform of N and P (Ramirez-cabral et al., 2017; Belfield and Brown, 2008). Water deficits can lead to delay in silking as well as kernel abortion. Similarly, flowering during hot and dry spelt periods leads to withering and death of silk. As a result, pollination and fertilization may fail due to pollen blasting hence seed set is significantly affected (GRDC, 2017; Nafziger, 2008).

Cob and kernel development stage (R2-R5): Development of cob, husks and shanks is completed 7 days after silking and plant requires enough water and nutrients to develop kernels on the cob. Kernels first appear as small blister structures filled with clear fluid (blister stage). As the kernel matures, the blister fluid becomes thicker and turns white in colour (milky stage) (Belfield and Brown, 2008). Both cob and husk are green at this stage and is the right time for use as green maize or roasting. The milk within the kernel then becomes thicker and changes into dough due to starch accumulation (dough stage). Nutrients (N and P) uptake is rapid during the kernel filling stages and exposure of the plant to low nutrient conditions at these stages results into reduced kernel size and low grain yield (VIB, 2017; GRDC, 2017; Belfield and Brown, 2008). Grain denting is observed about 20 days after silking which indicates that the embryo development is complete (dent stage) (Figure 17).

Physiological maturity stage (R6): Maize plant attains maximum dry weight (physiological maturity) 30 days after silking and accumulated dead cells form “black layer” at tip of each kernel. The black layer functions as a barrier to further absorption of assimilates (starch) into the kernel (Acquaah, 2012; Nafziger, 2008). At physiological maturity stage, milk line is disappeared with grain moisture content approaching 30%. While the shanks remain green, grain and husks lose moisture, followed by leaf drying. It is recommendable to begin harvest when grain moisture reaches 20% and grains should be dried to a grain moisture content of 13% or less for further use and storage (Acquaah, 2012).

ADAPTATION OF MAIZE AND YIELD POTENTIAL

Adaptation in maize is referred to as good performance in terms of yield and other agronomic characteristics under given environmental conditions (Brown et al., 1985). Maize is a universal cereal adapted to diverse

Table 4. Different environments under which maize crop is cultivated.

S/N	Environment	Description
1	Temperate	Latitudes 58° North to 30° South
2	Tropical	Latitudes 30° North to 30° South
3	Sub-tropical	Latitudes 30-34° North to 30-34° South
4	Altitude	From below sea level to 4000 meters above sea level
5	Soil type	Clay, silt-loam, sandy-loam, loamy and sandy
6	Soil pH	5 to 8
7	Soil drainage	Well
8	Relative humidity	70 to 90%
9	Rainfall	200 - 2000 mm
10	Day temperature	25 - 33°C
11	Night temperature	17- 23°C
12	Photoperiod (short day)	12.5 h

agroecologies of both temperate and tropical regions of the world from as far as 58° North up to 30° South, and can grow even at higher altitude of up to 4000 masl (Table 4). It It is a short-day plant with photoperiod of 12.5 h and relative humidity of 85 to 100%. Maize poorly performs under saline soils especially during flowering (Belfield and Brown, 2008; du Plessiss, 2003). Optimum soil pH for maize growth is 5.5 to 7 (AGOGTR, 2008; Government, 2018). Suitable temperature for optimum maize production ranges between 17 to 33°C and a minimum soil temperature of 12°C for germination. Maize is a widely adapted crop with high yield potentials (Ortega et al., 1980). Global average yield is reported at 4 t/ha (VIB, 2017). High productivity of maize is partly attributed to it being a C_4 plant; thus, it has modified anatomical and biochemical mechanisms that allow efficient use of carbondioxide for photosynthesis (Furbank, 2011; Sage, 2004; Fitter and Hay, 2002). Also, the bundle sheath cells have larger and richer chloroplasts which are useful for photosynthesis (AGOGTR, 2008). Maize plant has high water use efficiency of about 450 to 700 mm of water per season, which is mainly absorbed from the soil moisture content (Hamad et al., 2011; Nafziger, 2008). Single plant can consume up to 250 L of water during a life span with about 15.0 kg of grain produced per each millimetre of water consumed, provided normal agronomic practices are observed (du Plessiss, 2003).

Total leaf area at maturity may exceed one square metre per plant. Nutrient uptake by maize is highest at flowering stage such that at maturity the plant might have assimilated about 8.7 g of nitrogen, 5.1 g of phosphorus and 4.0 g of potassium respectively (du Plessiss, 2003). In addition to efficient use of water, maize uses sunlight more efficiently than any other crop, resulting into highest yield (kg/ha). Number of kernel rows per cob varies with a maximum of about 40 rows based on the maize varieties, and a total of 1000 kernels can be produced by a single maize cob. Number of cobs per plant normally ranges from 1 to 4 though other maize cultivars my bear up to 5 cobs per plant (Hoofpen and Maiga, 2012; du Plessiss, 2003). United States of America, China, Brazil and Mexico are the leading producing countries in the world with an average of more than 4 t/ha, contributing to about 563 million tonnes of the global total production of 717 million tonnes/year (Ramirez-cabral et al., 2017; Ranum et al., 2014). In SSA, average maize yield is lagging at about 2 t/ha, resulting into over 20% of the annual requirement being met through imports (ASARECA, 2014; VIB, 2017). Leading maize producers in Africa include South Africa, Nigeria, Ethiopia, Tanzania and Egypt (VIB, 2017).

MAIZE BREEDING

Maize is an important crop to millions of people around the world, especially in SSA and Latin America where it is the main source of food and income. A lot of effort has been directed towards improvement of the crop both nationally and internationally, through collaborations and research. Major international institutions and databases mandated to conduct research and disseminate technologies on maize include International Maize and Wheat Improvement Centre (CIMMYT) (http://ww.cimmyt.org); International Institute of Tropical Agriculture (IITA) (http://www.ita.org); FAO Crop and Grassland Service (AGPC) (http://www.fao.org/ag/AGP/AGPC/doc/crops); The Tropical Asian Maize Network (TAMNET) (http://www.tamnet.org); The Asian Maize Biotechnology Network (AMBIONET) (http://www.ambionet.prg); Maize genome (http://www.maizegenome.org/>); and Maize Genetics and Genomics database (http://www.maizedb.org/). Breeding of maize involves

Figure 18. Evaluation of low altitude hybrid maize genotypes selected from IITA for tolerance to low soil nitrogen in the greenbelt ecology of South Sudan.

selection of varieties by breeders and farmers for their desirable characteristics such as grain yield, plant height, silking date and tolerance to biotic and biotic stresses. Variety in maize is referred to as a specific kind of maize selected for use by farmers based on its desirable characteristics and it is maintained in its pure form through seed. So many maize varieties have been developed and some are available in the markets. Farmers adopt varieties based on market requirements, environmental conditions, management requirements, level of resistance to biotic and abiotic stresses, etc. (Espinoza and Ross, 2010; Kansas State University, 2007). The aforementioned factors are ever changing therefore, maize varieties are continually being improved or new ones developed to adapt to the new challenges. In SSA, a lot has been done on maize improvement and with efforts from IITA and CIMMYT, maize germplasm are freely available for improvement of maize varieties by national research institutions in the region (Figure 18). Available breeding procedures used for improvement of maize include conventional breeding, molecular breeding, mutation breeding and genetic modification (GMO) (AGOGTR, 2008; Fehr, 1991).

CONVENTIONAL BREEDING

In this approach, mainly selection is done under field conditions and it allows farmers and breeders to select superior maize varieties and maintain them for use under specific environments. Various selection methods such as mass selection (including recurrent selection), full-sib selection and half-sib selection are commonly used (Poehlman and Sleper, 1995; Fehr, 1991). Depending on the breeding objectives, conventional breeding is performed to obtain different outputs including open-pollinated variety (OPV), synthetic variety, composite variety and hybrid maize (Poehlman and Sleper, 1995).

Open-pollinated variety: Open-pollinated maize is obtained when selected lines with one or more characteristics in common are grown and allowed to undergo uncontrolled (open) pollination among themselves (Fehr, 1991). Maize is an out-crossing plant whereby when plants are grow in one field, chances of each plant pollinating itself is very low (AGOGTR, 2008).

Therefore, under open-pollination conditions, ovules on one ear of a plant can be pollinated with pollen from

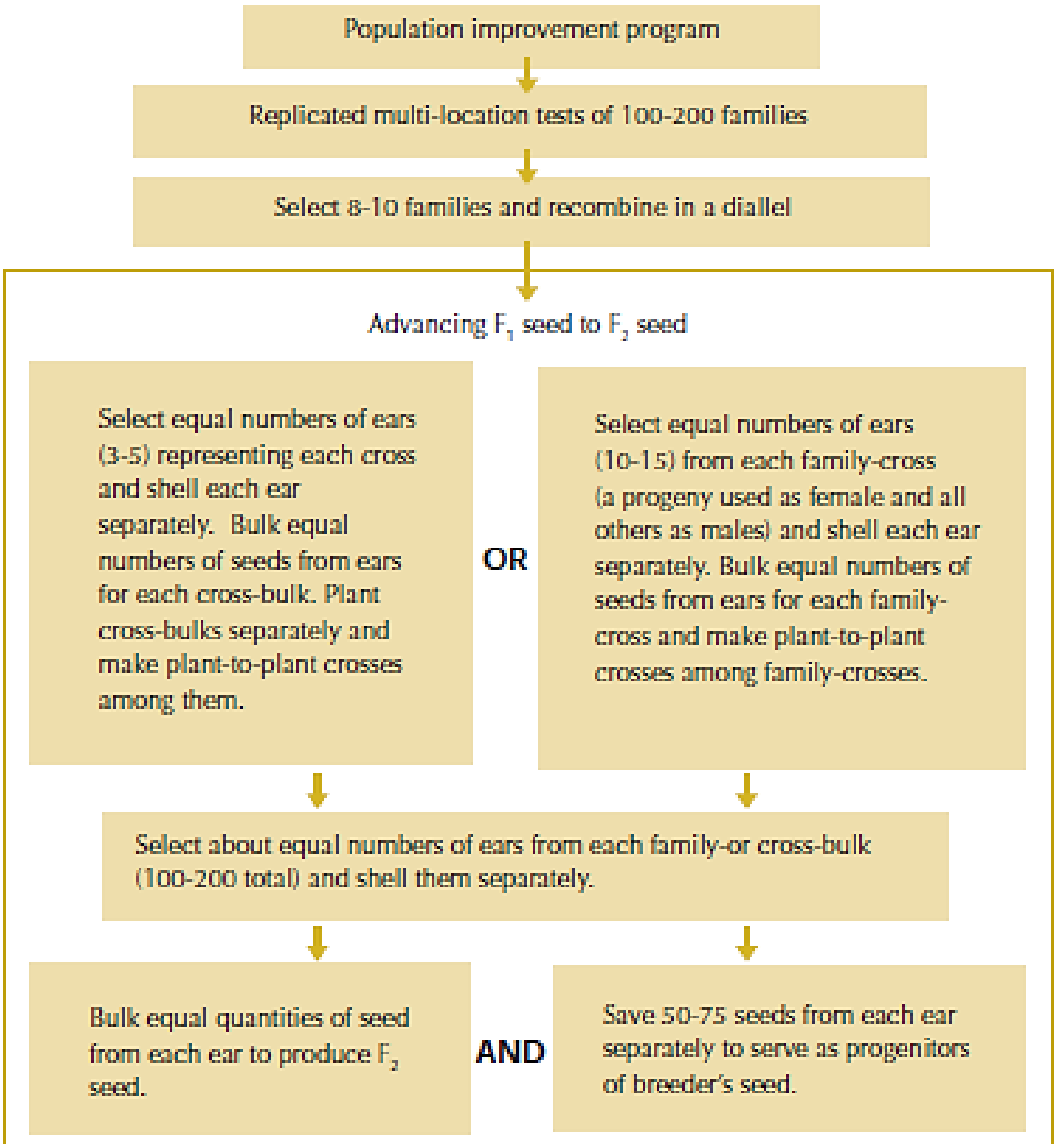

Figure 19. A simplified illustration of maize breeding showing OPV development under conventional approach (The Maize Program, 1999).

different plants. Consequently, grains on an ear are called OPV variety because they are from same female parent but different male parents (Brown and Caligari, 2008; The Maize Program, 1999). OPV varieties are genetically heterozygous and therefore, maize plants grown from OPV lack agronomic uniformity. Breeding for OPV is carried out using ear-to-row methods (The Maize Program,1999). First, a number of ears are harvested from a source population or selected from other sources based on their desirable characteristics. The ears are shelled, labelled and stored separately. Few seeds from each ear are planted in a separate row (ear-to-row) and evaluation is conducted for the traits of interest. Best performing rows are identified and their remnant seeds are mixed. The mixed seeds are planted in one field and allowed to open-pollinate among themselves (Figure 19). Ears from the open-pollinated field are harvested and desirable ears are again selected. Selected ears are shelled, labelled and stored separately and the process of ear-to-row begins again. The ear-to-row selection is repeated for 3-6 generations until OPV variety showing similarity in the target traits is formed (The Maize

Program, 1999; Poehlman and Sleper, 1995).

Synthetic: Synthetic is a variety which is developed when elite lines/parents selected for good combining ability are intermated in all possible combinations. First, lines are selected from population(s) based on their quality for the traits of interest for example, plant height, grain colour, etc. Selected lines are selfed then evaluated in replicated trials. Best performing lines are selected and crossed in half diallel scheme (Muraya et al., 2006). Data is analysed and lines with good general combining ability (GCA) for the traits of interest are identified. These lines are then planted in isolation from other maize fields and allowed to crosss-pollinate among themselves (open-pollination). The field is harvested and seed bulked to form synthetic variety. The new synthetic variety must be evaluated for agronomic performances across locations before final release (Andrés-Meza et al., 2017; Narro et al., 2012). Once released, breeder will constitute the synthetic in isolation by open-pollination (Fehr, 1991; Muntean et al., 2103; Welu, 2015). Synthetic variety is contrasted from OPV because: (i) it is formed by crosses in which sources of the pollen are known; and (ii) number of parents involved is small (narrow genetic base). As a result, synthetic variety is maintained in open-pollination only for few years and new stock is to be re-constituted from the original parents (Brown and Caligari, 2008). This is because synthetic stock loses vigor (heterozygosity) each generation due to increased inbreeding depression resulting from insufficient genetic diversity (that is, small number of parents involved) (Fehr, 1991).

Composite: Composite is a variety of maize developed by mixing different lines or germplasm selected previously for their uniformity in terms of height, maturity, grain colour, etc. Unlike synthetic variety, selection of lines for composite development does not require testing for combining ability (Chakraborty et al., 2011). In addition, number of lines involved in composite is more compared to the ones for synthetic. Usually, lines are selected and their seeds mixed and allowed to open-pollinate in isolation for 4-5 generations. In each generation, cleaning is done by removing out off-types (undesirable plants) so as to improve for target traits and uniformity. Lastly, the seed is harvested and tested including standard checks across locations, followed by release. Composite variety is maintained by open-pollination and farmers can save their own seeds for 3-4 generations (Hallauer et al., 2010).

Hybrid: Hybrid maize is a category of maize variety commonly used by both subsistence and commercial farmers and is the major driver in the success of maize in the modern farming systems and food security in SSA. Hybrid is developed by crossing two selected inbred lines with different genetic backgrounds to from a single maize plant (hybrid) (Poehlman and Sleper, 1995; Fehr, 1991). Economically, hybrid is preferred over other previous categories of mize varieties because hybrid can yield as high as 15% above the other varieties (OPV, synthetic and composite) (Setimela and Kosina, 2006). The superiority of hybrid maize over other categories is due to heterosis (hybrid vigor). Heterosis refers to increased performance of hybrid compared to its parents (Springer and Stupar, 2007; Brieger, 1949). The concept of heterosis in maize is centered on two main hypotheses. *Hypothesis I (Dominance theory)*: Heterosis is due to combination of dominant (favourable) alleles from the two parents when crossed. In the cross (hybrid), the favourable alleles mask the recessive (depressive or deleterious) alleles from both parents, leading to omission of depressive characters in phenotype of the hybrid. However, when the hybrid is selfed, the recessive genes are again reconstituted and reappear in the phenotype inform of depressed performance and loss of vigor (inbreeding depression). *Hypothesis II (Heterozygosis theory)*: Combination of different alleles in heterozygous form in a hybrid exerts a complementary physiological actions leading to hybrid vigor (Brieger, 1949).

Development of hybrid involves selection and testing of lines in experimental hybrid combinations (usually diallel or other similar mating designs) (Awata et al., 2018; Silva and Filho, 2003). Best hybrid combinations are identified and evaluated in multi locations for yield and agronomic performances. Lastly, seeds of the parents involved are increased as much as possible for production of hybrid seed for farmers. Concurrently, the parental lines are maintained by selfing in isolation. Major bottle neck in used of hybrid seed is that it cannot be recycled by farmers due to inbreeding depression. Therefore, new stock of hybrid seed must be constituted afresh for farmers to plant, the task which involves breeders and commercial seed companies. Different types of maize hybrids can be developed however, the most common in SSA include: (i) *Single cross hybrid* developed by crossing a parent line (A) by another parent line (B) = AxB; (ii) *Three-way cross hybrid* generated by crossing a single cross hybrid (AxB) by another third parent line (C) = (AxB)xC; and (iii) *Double cross hybrid* formed by crossing a single cross hybrid (AxB) by another single cross hybrid (CxD) = (AxB)x(CxD) (Table 5). Development of hybrid maize is a long task compared to the maize varieties developed through open-pollination. The breeder first identifies or develops inbred lines that have the target traits (Figure 20). Inbred lines are developed by repeated selfing or backcrossing of each parent over 6-8 generations until highest percentage of homozygosity (≈ 99%) is achieved (Yan et al., 2017). However, with the recent advances in breeding and genetics, time required to generate maize inbred lines can be significantly reduced (2-3 generations) by using

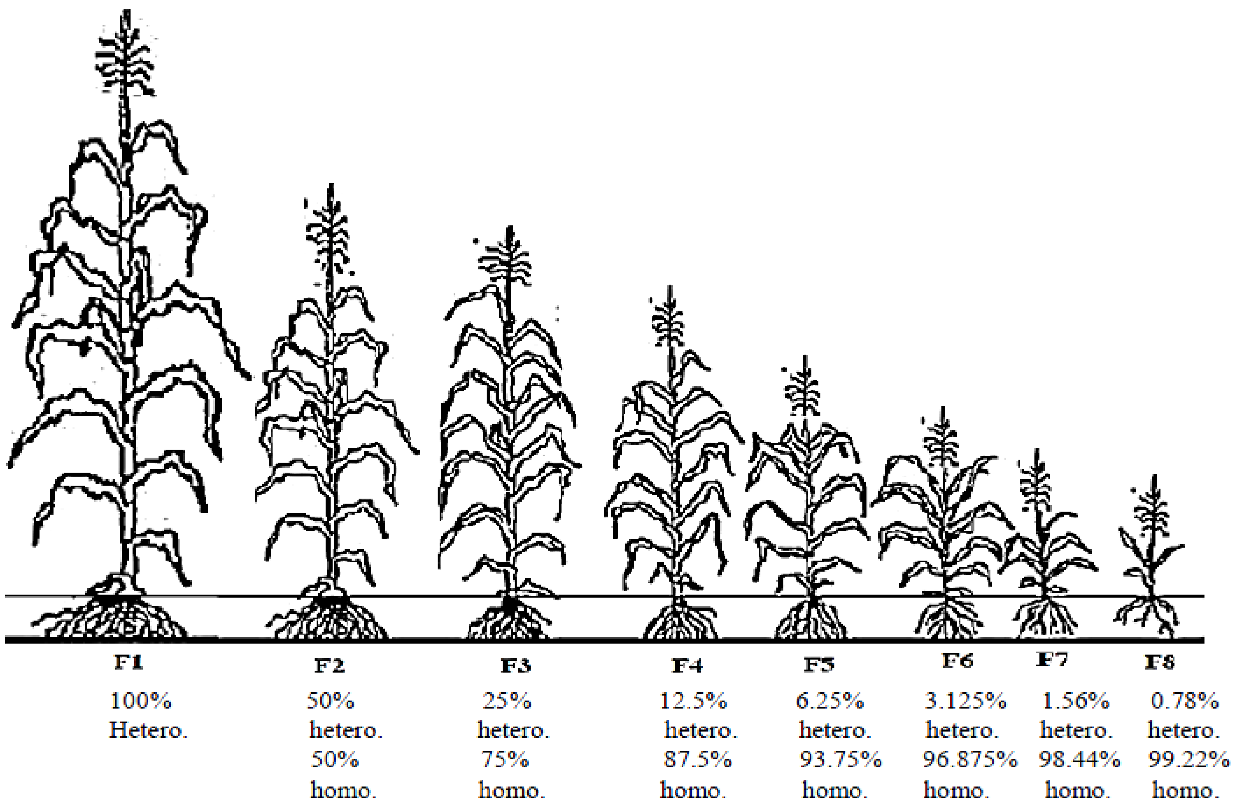

Figure 20. An illustration of conventional development of inbred lines by selfing (inbreeding) over 8 generations (Yan et al., 2017; Belfield and Brown, 2008).

Table 5. Common categories of hybrid maize seed commercially available for maize cultivation in sub-Sharan Africa.

SN	Hybrid category	Female parent	Male parent	Seed yield	Seed price	Hybrid characteristics	Grain yield (t/ha)
1	Single cross	Inbred line	Inbred line	Lowest	High	Uniform	High
2	Three-way cross	Single cross	Inbred line	High	Moderate	Slightly variable	Highest
3	Double cross	Single cross	Single cross	Highest	Low	Highly variable	Moderate to high
4	Top cross	OPV	Inbred line	Moderate	Low	Highly variable	Moderate
5	Varietal cross	OPV	OPV	Moderate to high	Low	Highly variable	Moderate to low

modern tools such as marker-assisted selection, doubled haploid (DH), mutation and GMO techniques (Yan et al., 2017; Prasanna et al., 2012).

MOLECULAR BREEDING

Organisms of same species share same genome but may differ in their chromosomal arrangements. This variability in genomic arrangement is referred to as molecular marker and has been extensively exploited by scientists (molecular breeding) to differentiate between individuals with respect to traits such as resistance to stresses, yield performance, etc. (Prasanna et al., 2010; Xu, 2010; Ye et al., 2009). Molecular breeding is a scientific approach based on identification of genetic variations (markers) that are linked to quantitative loci (QTL) associated with phenotypic characters or traits of interest. QTL are chromosomal regions or genes that control the traits of interest. Markers are usually validated through phenotypic observation under filed conditions so as to confirm the linkage between QTL and the trait (Berger et al., 2014; Liu et al., 2016). With the recent advances in science, molecular breeding has become a key approach for crop improvement and maize has benefitted the most. Common approaches employed in molecular research include marker assisted selection, marker assisted backcross, GMO and mutation breeding (Ruswandi et al., 2014; Waminal et al., 2013; Ye et al., 2009; Collard et al., 2005). For a successful molecular breeding, a mapping population developed from two contrasting homozygous or near isogenic parents is used (Xu, 2010; Semagn et al., 2006b; Landi et al., 2005). However, for open-pollinated crops such as maize, heterozygous parents can also be used. Different genetic markers are available but the most currently used include simple sequence repeat (SSR) and Single Nucleotide Polymorphism (SNP) (Rasheed et al., 2016; Semagn et al., 2006a; Collard et al., 2005). Various platforms such as genotyping-by-sequencing (GBS), next generation sequencing (NGS) and Kompetitive allele specific PCR (KASP) are used (Aglawe et al., 2017; Cao et al., 2017; Sudheesh et al., 2016). Various statistical methods are employed for association analysis however, regression analysis is more preferred because the value of coefficient of determination (R^2) of a QTL directly corresponds to phenotypic variability due to linkage of that QTL to the trait under study (Collard et al., 2005; Gelli et al., 2017; Semagn et al., 2010). Other commonly used methods include simple interval mapping (SIM) which simultaneously analyzes the interval between two adjacent markers (linked) on a chromosome; composite interval mapping (CIM) that combines marker regression with interval mapping, while incorporating additional information on markers; and multiple interval mapping (MIM) which uses multiple marker intervals simultaneously to fit multiple putative QTL. The method is also useful for estimating epitasis between QTL, genotypic values of individuals, and heritabilities of quantitative traits (Gelli et al., 2017; Jiang, 2013; Li et al., 2007).

DOUBLED HAPLOID BREEDING

Haploid is a spontaneous phenomenon found in various crop species including maize. It was first reported by Stadler and Randolph (1929 unpublished, Sarkar and Coe, 1966) with low haploid induction rate (HIR) of 0.1% however, inducer lines with as high HIR as 8-12% are now available (Dicu and Cristea, 2016; Khakwani et al., 2015; Dang, 2010; Prasanna et al., 2012). Haploids refer to plants carrying one pair of chromosome (n) which is then doubled to produce homozygous DH (2n) plants. Use of haploids enhances genetic gains where homozygous lines can be attained within 2-3 generations compared to conventional methods which can take up to 8 generations (Figure 21) (Rahman and de Jiménez, 2016; Begheyn et al., 2016; Bakhtiar et al., 2014; Gordillo and Geiger, 2010).

Haploids can be induced by *in vivo* through paternal and maternal haploid induction, or *invitro* (culture of immature male or female gametophytes) methods (Dwivedi et al., 2015; Gueye and Ndir, 2010). In maize, *in vivo* maternal haploid is the most commonly used technique in generation of DH lines. It is where inducer line is used as pollen source to produce maternal haploids (Dang, 2010; Jumbo et al., 2011; Odiyo et al., 2014). The procedures involve fertilization of F_1 or F_2 plant with pollen from haploid inducer line, usually done in a line x tested mating scheme (Awata et al., 2018; Odiyo et al., 2014). Haploid seeds can be visually separated from non-haploid seeds based on anthocyanin coloration. The technique exploits *R1*-Navajo (*R1-nj*) pigmentation which is a dominant anthocyanin marker, visually expressed in the aleurone (outermost maize the endosperm) and in the scutellum (embryo) of the haploid inducer (Khakwani et al., 2015; Prasanna et al., 2012). DH lines can be maintained by selfing or through sib-mating so as to maintain vigor of the lines (Dicu and Cristea, 2016; Jumbo et al., 2011). DH technique is increasingly being used in improvement of maize, with emphasis on generation of lines homozygous for superior agronomic traits (Bakhtiar et al., 2014; Wessels and Botes, 2014; Battistelli et al., 2013; Prigge, 2012).

POTENTIAL GENE TRANSFER IN MAIZE

Maize is a sexually reproducing organism with vertical gene transfer where gene is transferred from parent to the offspring during sexual reproduction. However, under controlled conditions, maize gene can be transferred to other organisms through sexual relationship (horizontal gene transfer) leading to fertile hybrids (AGOGTR, 2008; Hofmann et al., 2014). Common organisms between which horizontal gene transfer occurs with maize and produces viable hybrids are listed in Table 6. In all the crosses (except with teosintes where both plants can be used as sources of pollen) only maize is used as source of pollen.

MAIZE SEED PRODUCTION

Seed is any part of a crop that geminates or reproduces to become the same crop and which satisfies expectations in terms of the desired characteristics. Therefore, to enhance productivity, seed must be availed to farmers. However, maize is an out-crossing crop whereby, any seed (OPV or hybrid) production activity must strictly adhere to the rules and requirements. Various management practices and techniques have been adopted to generate maize seed with acceptable quantity and quality (Fehr, 1991).

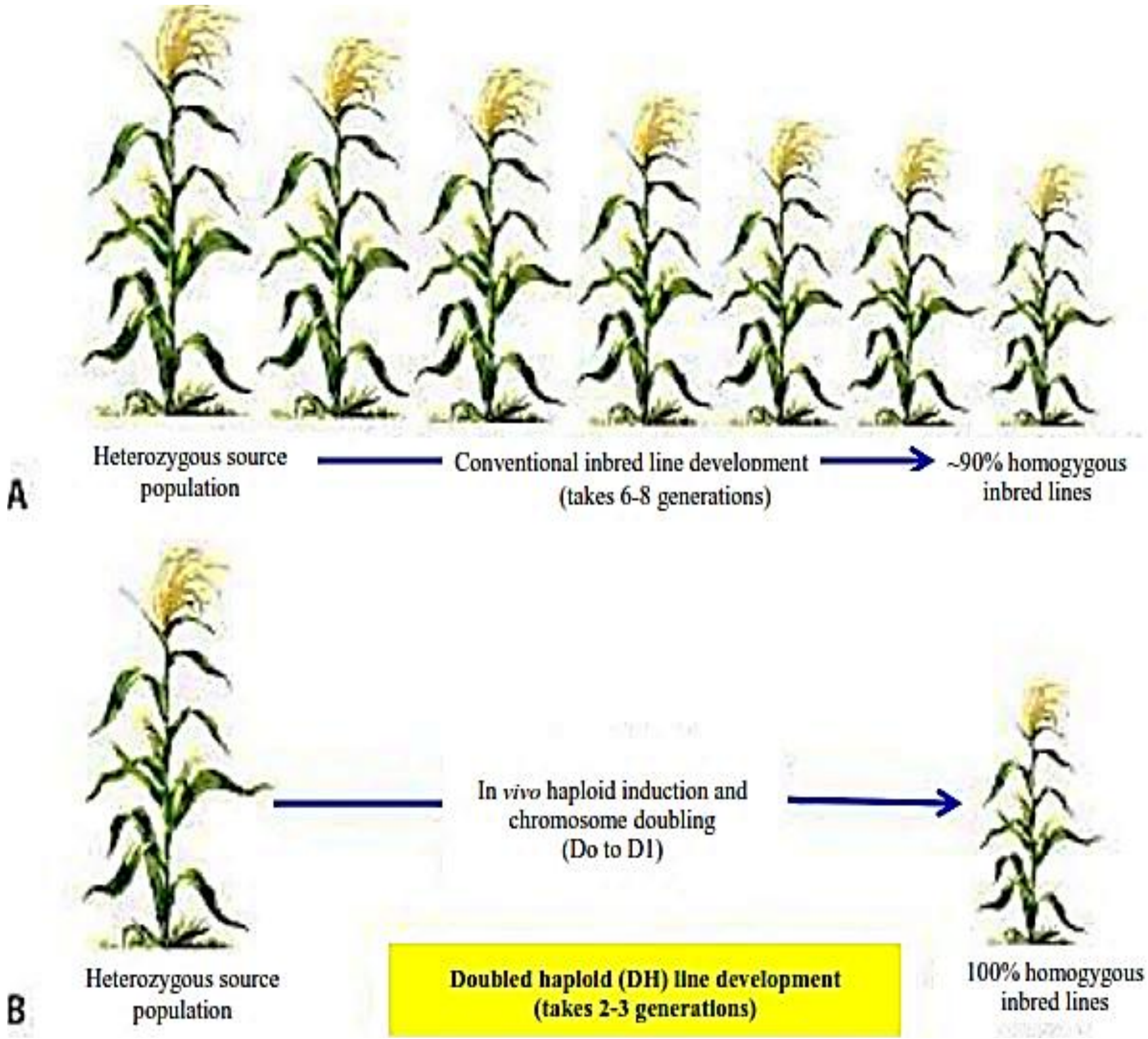

Figure 21. Production of maize inbred lines using conventional and doubled haploid approaches. A = Representation of conventional method of development of maize inbred lines. Conventional development of inbred lines requires 6-8 generations of selfing. The procedure is time consuming and economically expensive. B = Illustration of development of maize inbred lines using DH technique. DH method is faster and takes only 2-3 generations to convert heterozygous lines into pure inbred lines. The technique is gaining popularity especially in maize breeding **Source:** (Prasanna et al., 2012).

Table 6. Crosses between maize (*Zea mays* L.) and some species that produce viable hybrids.

Hybridization	Remarks
Zea mays×all teosintes (except *Zea perennis*)	Hybridization occurs naturally, high success with teosinte as pollen source
Zea mays×*tripsacum* spp.	Hybridization occurs under controlled conditions
Zea mays×*Coix lachrymal-jobi*	Hybridization occurs under controlled conditions
Zea mays×*Saccharum officinarum* (Sugarcane)	Hybridization occurs under controlled conditions
Zea mays×*Triticum aestivum* (Wheat)	Hybridization occurs under controlled conditions, embryo rescue required
Zea mays×*Avenasativa* (Oat)	Hybridization occurs under controlled conditions, embryo rescue required
Zea mays×*Hordeum vulgare* (Barley)	Hybridization occurs under controlled conditions, embryo rescue required
Zea mays×*Secale cereale* (Rye)	Hybridization occurs under controlled conditions, embryo rescue required

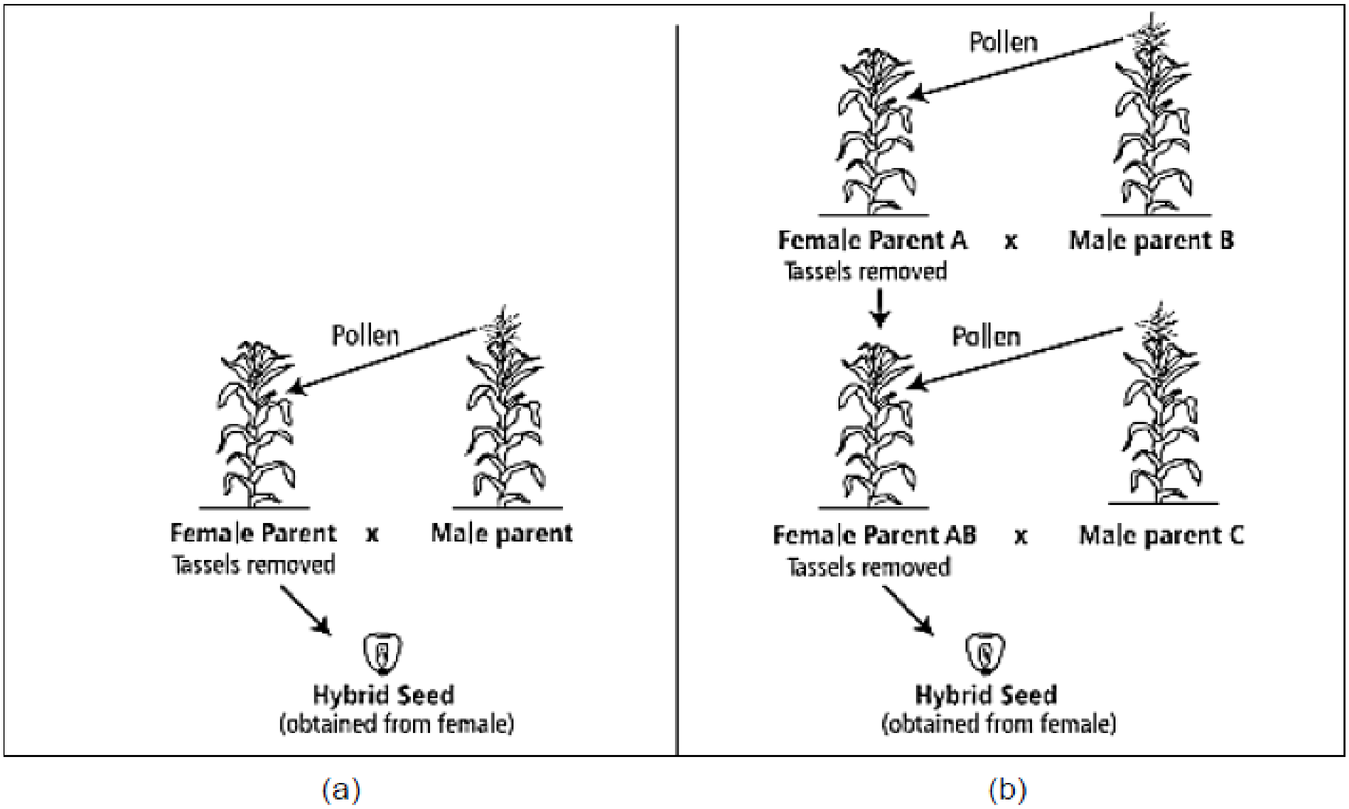

Figure 22. Illustration of procedures involved in hybrid maize seed production. (a) Production of single cross hybrid using two inbred parents of similar maturity. Female parent is detasseled before pollen shed and then pollinated with pollen from the male parent. Pollination is carried out by hand and single cross seed is harvested. (b) Production of three-way hybrid. The single cross seed is planted as female while another inbred line is planted as male parent. The female parent is detasseled and then fertilized with pollen from the male parent (Setimela and Kosina, 2006).

UNCONTROLLED SEED PRODUCTION

Uncontrolled seed production referred to the conditions where maize is planted in isolation and allowed to cross-pollinate, followed by harvest of seed at the end of the season. These categories of seed include OPV, synthetic and composite (Setimela and Kosina, 2006; Fehr, 1991). The categories can be produced by both seed companies and farmers. However, depending on each country, production by the later requires strict supervision by seed extension agents or breeders.

HYBRID SEED PRODUCTION

Hybrid maize seed is a corner stone in the elevation of agricultural production and food security in SSA. Successful hybrid seed production must satisfy the following requirements: (i) high manifestation of heterosis; (ii) ease of control of pollen flow from the female; (iii) ease of transfer of pollen from male to female plant; and (iv) reliability and economic of the investment (Fehr, 1991). Usually, male and female lines are planted in the same block in the ratio of 1-2 lines of male: 3-6 lines of female (Setimela and Kosina, 2006). To avoid pollen flow from female lines, any female tassel is removed out the day the tassel is about to emerge (Figure 22). However, under large scale hybrid seed production, control of sources of pollen becomes hectic. Cytoplasmic male sterility has become a powerful technology to address this shortcoming (Fehr, 1991; Islam et al., 2015).

CYTOPLASMIC MALE STERILITY

Cytoplasmic male sterility (CMS) refers to the inability of a normal plant to develop viable pollen or other reproductive cells due to mitochondrial dysfunctions (Vinod, 2005; Wise et al., 1999). CMS can appear spontaneously in a breeding line due to mutation in nuclear or cytoplasmic genes. For, example, male-sterile Texas cytoplasm in maize was a result of a spontaneously occurrence in a breeding line (Islam et al.,

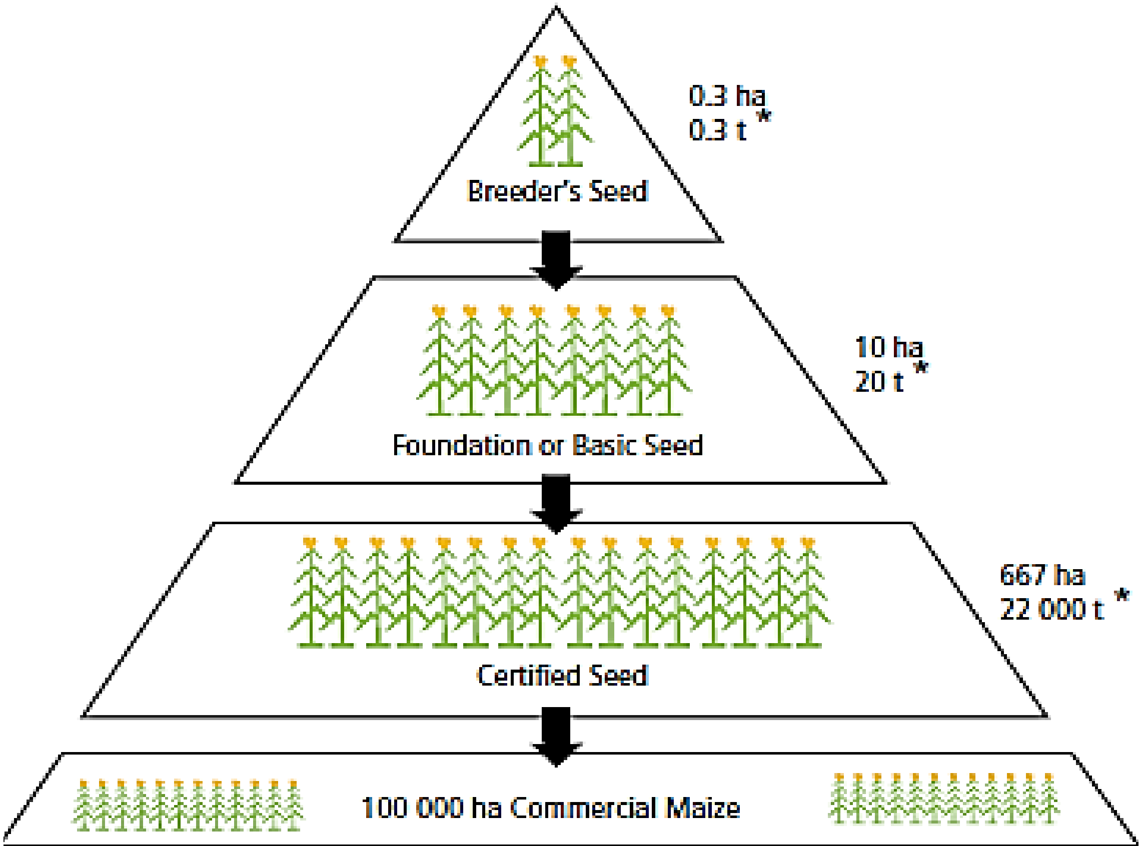

Figure 23. Different stages of seed production and their respective field sizes. Breeder's seed is usually the smallest in quantity and thus requires small area for production (Setimela and Kosina, 2006).

2015; Wise et al., 1999). However, commercial CMS lines are now available in the markets. Gene causing CMS (dysfunction) is recessive, maternally inherited and is found within the open reading frame (ORF) of the mitochondria genome (Fehr, 1991; Islam et al., 2015; Sofi et al., 2007; Vinod, 2005). The genetic mechanisms of CMS have been discussed in detail elsewhere (Acquaah, 2012; Begheyn et al., 2016; Wise et al., 1999). Maize lines with CMS cannot self-pollinate themselves hence rely on other plants for their pollination (Vinod, 2005). The technology is widely employed in commercial hybrid seed production in maize (Islam et al., 2015; Sofi et al., 2007; Wise et al., 1999; Fehr, 1991).

CLASSES OF MAIZE SEED

Clear understanding of different classes of maize seed is crucial for any formal seed system and effective seed value chain. According to international seed certification rules (OECD and ISTA), maize seed is categorized into five classes including pre-basic seed, basic seed, first or second generation certified seed, and quality declared seed (QDS) (Fehr, 1991; OECD, 2018; Setimela and Kosina, 2006). Usually, field size required for production of seed increases as we advance from pre-basic to certified seed stages (Figure 23). This is because a lot larger quantity of foundation seed is required so that many seed companies can access any quantity they want. The last category is the certified seed which occupies the largest area in terms of production. Certified seed is usually produced in hundreds or thousands of tons, depending on capacity of the seed companies. This is because certified seed is the one that local farmers need to plant for food production.

PRE-BASIC SEED

Also referred to as breeder's seed, pre-basic seed is the nucleus of all classes of seed used for commercial cultivation. Pre-basic seed is owned by the breeder that develop the seed or by the institution. It is maintained by self-pollination or by planting in isolation then allowed the plants to cross-pollinate themselves. To avoid planting every season, breeder's seed can be stored under low temperature for 2-3 seasons.

BASIC (FOUNDATION) SEED

This is also referred to as foundation seed and is produced when breeder seed is planted in big field. Production of basic seed should be based on demands from seed companied and farmers. In case of other categories of seed (except hybrid), multiplication of basic seed can be carried out by both farmer groups and seed companies. For hybrid seed production, two forms of basic seeds (single cross female parent and inbred male parent) are involved (Chakraborty et al., 2011; Fehr, 1991; Setimela and Kosina, 2006). Therefore, the single cross female parent is produced by the breeder and sold to seed company while the male parent can be bulked by both breeder and the seed companies. Generally, basic seed is used to produce first generation certified seed.

FIRST GENERATION OR SECOND GENERATION CERTIFIED SEED

This is the quantity of seed produced by seed companies using the basic seed. It is also referred to in literatures as first degree or second degree certified seed. It is the one that farmers buy from agrodealers and use for grain production. Sometimes, remnant from first generation certified seed is planted the next season to produce second generation certified seed which is then sold to farmers (Fehr, 1991).

QUALITY DECLARED SEED

Seed is a precious element of agricultural productivity and farmers are entitled to access of quality seed for improved production. In SSA, this is seldom achieved by farmers especially the resource-poor farmers and those in country sides where formal seed system is lacking (Gildemacher et al., 2017; FAO, 2006). To address this issue, QDS has been introduced as a class of seed that farmers can access. Usually, QDS is produced under local regulations that are less rigorous than the conventional seed certification rules, but ensure that basic quality of seed is maintained hence increasing access to quality seed by smallholder farmers (OECD, 2018; OECD Seed Scheme, 2012; Wageningen University and Research, 2015). General guidelines which can be adapted for QDS production under specific conditions have been developed by FAO (FAO, 2006). Under the guidelines, monitoring and regulation to ensure seed quality is conducted voluntarily (self-control) by individual farmers or by group of farmers (Gildemacher et al., 2017). No external directive is required. However, national seed inspection services can conduct random sampling of some seed farmers to confirm that the seed meets QDS standards, followed by declaration of the stock as quality seed (FAO, 2006). The QDS is used locally by smallholder farmers as it cannot compete with the high quality certified seeds. Though QDS is not suitable for hybrid maize seed production, it has been effective for OPV maize and other self-pollinated crops such as beans, groundnut, sorghum, potato and cassava cuttings (Gebremedhin et al., 2016; Gildemacher et al., 2017; Louwaars et al., 2016).

MAIZE GERMPLASM AND THEIR AGRO-CLIMATIC ZONES

Various maize germplasm are available within maize growing zones around the world and are grouped according to their agro-climatic adaptations based on maturity. Major maize germplasm fall within the tropical (low/highlands), sub-tropical and temperate categories (Table 7). Maize grown in SSA are mainly of white grain types belonging to the tropical and sub-tropical, medium to late maturity groups (Brown et al., 1985; Ortega et al., 1980).

CULTURAL PRACTICES AND MANAGEMENT

Maize is a field crop adapted to cultural practices under different conditions. The crop can easily be grown singly or mixed with other crops such as cassava and legumes (Hoofpen and Maiga, 2012; Belfield and Brown, 2008). Like most cereal crops, maize requires appropriate cultural practices and management so as to realize maximum yield.

LAND PREPARATION

Land preparation is the process by which a piece of land is made suitable for planting of seed. It involves bush clearance and tilling of soil. In land that is not covered with thick bushes or one that has been cultivated the previous season, bush clearance may not be necessary. Soil tillage is a farming system referring to physical soil cultivation practices resulting into change in soil structure, hydraulic properties and stability, so as to allow optimum plant growth (du Plessiss, 2003). Conventionally, and for better crop establishment, tillage is performed 1-3 times depending on the field conditions. The field should be tilled to a suitable depth of 10-20 cm in order to allow optimum water absorption, root development and crop establishment (Espinoza and Ross, 2010; Belfield and Brown, 2008). Soil tillage enhances water infiltration and aeration which are vital for plant growth and

Table 7. Agro-climatic characteristics considered in classification of maze germplasm.

Maturity class	Altitude (masl)	Latitude N-S (degrees)	Mean temperature of growing season (°C)			No. days to physiological maturity
			Min	Max	Av.	
Tropical lowland						
Early	Below 100	Within 23	22	32	28	±80
Medium	Below 100	Within 23	22	32	28	±100
Late	Below 100	Within 23	22	32	28	±120
Tropical highland						
Early	Above 1800	Within 23	7	22	16	±150
Medium	Above 1800	Within 23	7	22	16	±180
Late	Above 1800	Within 23	7	22	16	±220
Sub-tropical						
Early	Below 1800	Within 34	17	32	25	±100
Medium	Below 1800	Within 34	17	32	25	±130
Late	Below 1800	Within 34	17	32	25	±160
Temperate						
Early	Below 500	Outside 34	14	24	20	±110
Medium	Below 500	Outside 34	14	24	20	±130
Late	Below 500	Outside 34	14	24	20	±160

Adapted from Ortega et al. (1980).

development. After tillage is complete, harrowing is performed so as to level the field such that seed can be planted on suitable bed. Care should be taken not to level the seed bed so smooth such that run-off can occur. A variety of implements including hand hoe are commercially available to farmers for land preparation in SSA. Common among them include mouldboard ploughs, disc ploughs and discs, chisel ploughs and harrows, oxen-driven and hand hoe (World Bank, 2012; Izge and Dugje, 2011; du Plessiss, 2003). In places where weed is not a major problem and soil erosion is not common, farmers may adopt minimum or no-tillage systems of maize cultivation. No-tillage involves a practice where seed is directly planted into the field without tilling and the soil is left undisturbed until harvest (Acquaah, 2012; Espinoza and Ross, 2010; Nafziger, 2008). Different minimum soil tillage practices are being adopted where soil is partly tilled and weed control is mostly by chemicals (Table 8).

PLANTING

Planting is the exercise of putting seed into seed bed for an intended crop growth and development. Maize planting commences as soon as land preparation is complete and suitable soil moisture and temperature availed. Maize planted on soil with unfavourable environmental conditions such as drought, excessive water, and extreme soil temperatures may fail to germinate hence dies. Normal planting depth for maize is 5 cm (heavy soil) to 10 cm (sandy soil). Other practices include spacing and plant population size. The plant population size is determined based on rain fed or irrigated systems, prevailing environmental conditions and variety used (AGOGTR, 2008). Maize planted under irrigation usually has high plant density compared to rain fed system (Table 9).

WATER MANAGEMENT

Maize plant is adapted to wider environments including rain-fed and irrigated conditions. Under irrigation, water management is essential and if well managed, grain yield can be as high as 20 tons per hectare (t/ha) (du Plessiss, 2003). Different irrigation equipment used in SSA includes sprinklers and drip irrigation. Irrigation regime should be set based on the growth stage, soil type and prevailing environmental conditions, and pumping capacity of the equipment (Yenesew and Tilllahun, 2009; Rhoads, 1991).

WEED MANAGEMENT

Weed is any plant/grass growing in the maize field and which is not intended to be there since it competes with maize plant for water and nutrients, leading to poor yield. Weed is one of the major constraints facing maize

Table 8. Common soil tillage systems with their advantages and disadvantages.

Tillage system	Advantage	Disadvantage
No-till	• Lowest fuel consumption • Quicker adaptation to optimum planting date • Lower machinery costs • Best control of wind and water erosion	• Higher application of herbicide and intensive herbicide management • Requires: –management inputs –special or adapted planters –more expensive equipment • Possible compaction of soil and accumulation of nutrients in topsoil • Earlier occurrence of leaf diseases • Possible increase in insect populations
Stubble- mulching	•Fuel saving (compared to ploughing) •Good control/better management of: –wind and water erosion –soil compaction –weed control	• Soil preparation dependent on rains • Greater possibility of leaf diseases
Reduced tillage	• Greater fuel economy compared to ploughing • Control of: –wind erosion –insect population • Accumulation of nutrients not a problem	• Poor management of water erosion • Poor weed management
Conventional tillage	• Good weed and insect control • Lowest management inputs	• Highest: –fuel consumption –machinery costs • Waiting period for suitable soil water • No control of water and wind erosion

Source: (du Plessiss, 2003).

Table 9. Planting practices adopted by famers for growing of maize in sub-Saharan Africa.

Practice	Standard
Planting depth	5 to 10 cm
Row spacing	75 to 100 cm
Hill spacing	25 to 50 cm
Seed per hill	1 to 2
Plant population per ha (rainfed)	20,000 to 53,333
Plant population per ha (irrigated)	60,000 to 80, 000
Plant population per ha (silage-rainfed)	50,000 to 60,000
Plant population per ha (silage-irrigated)	70,000 to 100,000

production worldwide (Suleiman and Rosentrater, 2015; du Plessiss, 2003). Proper management of weed is a prerequisite for maximum maize yield. Common weed management practices in SSA include mechanical removal of weeds by hand hoe or machine, use of herbicides to kill the weed and good agronomic practices such as use of clean seed (Chakraborty et al., 2011; Belfield and Brown, 2008). Various chemicals under different commercial names such as Atrazine, Imazethpyr+imazapyr and Imazapyr+pyrithiobac are being effectively used for pre- and post-emergence weed control in maize (AGOGTR, 2008; Chakraborty et al., 2011). Weeding can also be done by machine provided row spacing is large. Depending on field conditions, weeding of maize field can be conducted 2 to 3 times during the vegetative stages and before maturity. First weeding is normally done 2 weeks after seeding emergence, followed by second weeding before flowering and the last one during or immediately after flowering. It is a good practice to keep an eye on maize field so that any weed that might have escaped weeding is pulled out manually.

NUTRIENT MANAGEMENT

Maize is an aggressive consumer of soil nutrients due to its nature of growth and development. Normally, maize field is supplemented with nutrients in form of inorganic fertilizers (though organic fertilizers are also applicable) (Vanlauwe et al., 2011; Espinoza and Ross, 2010). The organic fertilizers are found inform of manures and have not been commonly used for fertility supplementation in maize due to its bulkiness which poses difficulties in management since maize is always planted in big area. It is important that before any fertilizer application, nutrient requirements of the soil be correctly determined through soil analysis and correct recommendation of fertilizer rates given inform of kilogram per hectare (kg/ha) (Saïdou et al., 2017; Espinoza and Ross, 2010). Farmers should strictly adhere to the recommendations from the soil analysis so as to obtain good results in the field. Incorrect application of fertilizer negatively impacts on soil physical properties and chemical composition, leading to poor maize yield (du Plessiss, 2003). Major inorganic fertilizers used to supplement maize nutrients include urea (N), phosphorus (P), potassium (K) and zinc (Zn) with each differs in its requirement and time of application.

Nitrogen fertilizer (N): Nitrogen fertilizer is critical for healthy growth and development of maize and can be applied 2-3 times during maize growth period. First application is during planting where the fertilizer is placed 50 mm in soil below and by the side of the seed then buried. Second application comes two weeks after seedling emergence followed by the third application to be administered just before or during flowering. Third application is very crucial because at this stage maize plant requires a lot of energy to perform the multi tasks of growth and reproduction (Espinoza and Ross, 2010). Both second and third applications are conducted by topdressing (that is, putting the required quantity of N on top of the soil and 100 mm away from the plant. Direct contact between N and the plant leads to plant burn and sometimes death. Residual soil N and weather conditions affect requirement and application of N. When N is applied and the soil continues to remain dry, the fertilizer will be lost due to heat and evaporation and the plant will not benefit. Therefore, it is recommended that N should be applied while the soil is moist. For topdressing, N should be administered after rain or when rain is about to fall however, when the weather is humid especially in late afternoon, the fertilizer can be applied. In addition, it is advisable to apply N after weeding to avoid competition between maize and the weeds. Quantity of N (kg) applied per ha varies depending on the soil requirements, residual N in the soil and plant population (Saïdou et al., 2017). Nitrogen fertilizer is sold in the markets informs of urea, NPK and CAN (Espinoza and Ross, 2010). Nitrogen deficiency in the soil can be recognized by pale to light green appearance of young maize plant in the field. Also, at later stage, older leaves show inverted V-shape and yellowing (du Plessiss, 2003).

Phosphorus (P): Phosphorus is an important element for maize growth and establishment. The fertilizer is applied at planting at 50 mm below the seed and at the seed side then buried. Unlike N, P is applied just once for the whole of maize growth in the field. Phosphorus plays key role in providing nutrients to young maize seedling since at this early stage, the seedling has undeveloped root system hence unable to absorb its own nutrients from the soil (Espinoza and Ross, 2010). Phosphorus fertilizer is commonly available in the markets informs of di-ammonium phosphate (DAP) and NPK. Maize plant lacking P can manifests dark green leaves with reddish-purple tips and margins, especially when the plant is still young. However, maize seedling also shows purple symptoms when soil temperature drops below 12°C. This is because under cold conditions, soil cannot release P to plant (du Plessiss, 2003). Therefore, prior to adding P to the field, care should be taken to understand whether the purple symptom is due to lack of P in the soil or due to low soil temperature.

Potassium (K): Like the above fertilizers, K should be placed 50 mm below and beside the seed during planting. Also the application is done just once. A quantity of 30 to 50 kg of K is appropriate for 1 ha depending on the soil requirements. Potassium fertilizer is commercially available as Potash and NPK (Espinoza and Ross, 2010). Lack of K in the soil is reflected as yellowing or necrotic leaf margins starting from lower leaves and progresses upwards to younger leaves (du Plessiss, 2003). The deficiency has also been implicated in stalk rot and lodging in maize.

Zinc (Zn): Zinc is another important micro element required for good maize growth and development. Application of Zn is similar to the procedures followed for P and K above. Deficiency in Zn is observed on maize plant as light streaks between leaf veins while mid rib and leaf tip remain green, leading to stunted growth

(AGOGTR, 2008; du Plessiss, 2003).

INSECT/PEST MANAGEMENT

Insects and pests of maize refer to those organisms that feed on maize and cause significant yield losses (t/ha) or reduction in quality of stored grain. A great number of insects and pests of maize has been reported (VIB, 2017; Espinoza and Ross, 2010; AGOGTR, 2008) (Appendix 1). Better control of insect/pest of maize is achieved through application of ‘integrated pest management’ system. This is where pest population is suppressed using a combination of practices including chemical control, biological control, host resistance and cultivation control. Some animals and birds are also known to attack maize and cause great damages and yield losses (AGOGTR, 2008).

Chemical control: Insects/pests cause significant yield reduction in maize in SSA. Various chemicals have been effectively used for control of the organisms though costs of buying chemicals, for example, pesticides are usually high that most farmers can not afford (VIB, 2017; Karavina, 2014; Karaya at al., 2009). However, chemical control is effective especially when maize is grown under irrigated system. Commonly used chemicals for pests control in maize fields include Abamectin + Chlorantraniliprole (for example, Voliam Targo 063 SC), Lufenuron (for example, Match 50EC), Chlorantraniliprole (for example, Coragen 20SC), Emamectin benzoate (for example, Prove 1.92EC), Pyriproxyfen (for example, Profen 10.8EC) and Acephate (for example, Orthene Pellet) (Prasanna et al., 2018).

Biological control: Different organisms use maize plant as part of their ecosystem in order to survive and perpetuate. This relationship sometimes leads to competition among themselves as a result, the stronger organisms (natural enemies or beneficial insects) displace or kill the weaker ones (preys). The concept has become to be known as biological control, and can be successfully used for reducing insect/pest population in maize fields (Ruocco et al., 2010). For example, ladybird insect can feed on aphids leading to reduction in population of the latter in the field. Also population of beneficial insects can be enhanced by spraying maize field with chemicals (insecticides) which are non-toxic to the natural enemies but kill the pests (du Plessiss, 2003).

Host resistance: Management of insects/pests of maize in the field through various strategies is becoming an economical burden. For example, use of pesticides poses great global challenges due to its effects on environment and human health. In addition, chemicals are usually expensive and most farmers are unable to buy. Host plant resistance provides much effective and economically practical option for maize production in SSA, especially among the resource-poor farmers (Badji et al., 2018; CAB International, 2015; Willcox et al., 2002). Host resistance is the genetic ability of a plant to respond to pest attacks such that yield and other agronomic performances are not compromised. The strategy has been effectively used to control insects/pests in maize for example, insect resistant maize varieties can be planted (Badji et al., 2018; Izlar, 2014; Munkvold and Hellmich, 1999).

Cultivation control: Cultural practices such as soil ploughing, digging and proper weeding can destroy pests and their eggs that are laid in the soil. Destruction of crop residues, removal of volunteer plants, cop rotation and good timing of planting date can help suppress pest population in maize field.

DISEASE MANAGEMENT

Maize, due to its wide adaptation, has attracted various pathogens including bacteria, fungi, viruses and mycotoxins that cause significant yield losses all over the world (Appendix 2). This presents a serious threat to food security and livelihood especially in SSA where over 80% of the population depends on maize as source of food (VIB, 2017; Mahuku et al., 2015; Magenya et al., 2008). For example, mycotoxins which are special compounds that cannot be neutralized by processing, can affect both human and animals. Depending on concentration of the toxins in food or feed, it causes serious health implications and even death in certain cases (Okoth et al., 2017; Mwalwayo et al., 2016; Mutiga et al., 2015). Each region/country has its own level of acceptable percentage of mycotoxin contamination in food/feed (AGOGTR, 2008; Wu et al., 2018). Like for insect/pest management, similar practices can be applied for disease management especially for insect/pest transmitted viral diseases. These include use of fungicides, crop rotation, host plant resistant, weeding, and removal and burning of infected plants (Hell et al., 2014; Tamirat et al., 2014). In case of severe or endemic disease outbreak, movement into and within the field is highly restricted so as to avoid infections and disease spread.

MAIZE HARVEST

Careful and timely harvesting of maize is an important factor towards good yield. Even after maize matures with good cobs in the field, yet with careless harvest, most of the cobs or grains will be left in the field leading to low yield outcome. Maize harvest is usually conducted manually (by hand) though some few commercial

Figure 24. Maize field showing combined harvester during harvest.

producers use machines such as combined harvesters.

Manual (hand) harvest: Hand harvesting of maize is a very efficient way of removing ears from the field however, it is labour intensive. Maize is allowed to completely dry in the field then the ears are manually picked and collected in bags. It is advisable to carry out harvest as soon as the maize is dry and before the plants start falling down. Late harvest, when many plants have lodged, will lead to yield loss as ears on the ground may not be picked by the labourers, especially when the field is weedy. Also, over delay of harvest when the weather is cool may lead to ear infections by mycotoxin producing fungi (AGOGTR, 2008). Harvested ears are carried in bags to the drying space and allowed to dry for some few days. Based on the intended use, the ears are sorted accordingly and threshed before storing. Time for harvest can be determined by randomly sampling the ears and testing their grain moisture content. Right grain moisture content to begin harvest is 18-20% followed by further drying after harvest (AGOGTR, 2008). Sometimes, the whole plant is cut while green (at physiological maturity with grain moisture content of 28 to 34%) and allowed to dry in one place. Later ears are removed and threshed (du Plessiss, 2003). This method is useful where rainy seasons are short and farmer wants to plant another season as soon as possible. Maize planted for silage is harvested at vegetative stage when the dry matter content is about 30 to 35% (AGOGTR, 2008).

Mechanical harvest: Maize harvesting is a tedious task as dry maize in the field is able to withstand field conditions for only 5-15 days from the date it reaches harvest period. Beyond which the plant can fall down due to different factors leading to yield loss (Chiaranaikul, 2009; Miodragovic and Djevic, 2006). Therefore, harvest should be completed as fast as possible. This is more critical especially for commercial farming in which maize fields are extremely large and hand harvesting may take many weeks. Use of mechanical methods can significantly reduce the time for harvest as well as loss of grains in the field. The most commonly used maize harvesting machine is a combined harvester (Figure 24). Some combined harvesters are equipped with implements that allow harvesting, processing and packaging of grains at the same time (Chiaranaikul, 2009).

Grain drying, processing and storage: Immediately after harvest, maize grain should be dried, processed and packed. These last procedures are essential for quality and life span of grain. Drying is conducted naturally in open or dry and well ventilated space where grain is allowed to dry for 3-5 days. Sometimes, farmers enhance the drying by exposing the grains to direct sunlight for 1-2 days. Smallholder farmers usually store their produce in locally constructed structures (Figure 25). For commercial farming with large scale production, drying may be enhanced artificially using electrified systems (Kenneth and Hellevang, 2013). Under natural conditions, maize grain is allowed to dry until the moisture in the grain is in balance (equilibrium moisture content, EMC) with that in the atmosphere. EMC of maize grain for long and short term storage ranges between 12-15% and is advisable to confirm the moisture content using moisture meter (Kenneth and Hellevang, 2013; Sadaka and Bautista, 2012).

Dry grains can be processed manually or using automated seed processing unit in case of large scale production. Seed is sorted accordingly and packed in relevant sizes based on ease of management and market demands. Processed grain is stored in clean stores following proper treatment with recommended chemicals to prevent insect attacks. Various chemicals used for control of insects/pests in store include methyl bromide, chloropicrin, acetic acids, propionic acids, phosphate gas, calcium propionate, potassium sorbate, sodium propionate and sodium sorbate (Morais et al.,

Figure 25. Local granary structure commonly adopted by smallholder farmers for storage of grains in SSA (VIB, 2017).

2017; Coradi et al., 2016; Likhayo et al., 2014). This is important as insect/pests such as weevils and rats will be controlled. Normally, bags of grains are stacked on pellets so as to avoid direct contact between grain and the floor, and to enhance aeration. Similarly, roof of the store is to be filled with air ventilators to allow air movement. Maize grains can also be stored in air-tight contains/bags where insects/pests cannot be able to survive due to lack of oxygen. Generally, grains with moisture content below 12.5% stay longer in the store. Sometimes, due to lack of storage facilities, farmers in rural areas have developed skills to store their produce by hanging unshelled cobs overhead.

MAJOR CONSTRAINTS TO MAIZE PRODUCTION IN SUB-SAHARAN AFRICA

Maize is widely cultivated in different agro-ecologies of SSA; however, average yield (t/ha) in farmer fields remains low compared to those in developed world (AGRA, 2017). Major constraints to maize production in Africa include biotic and abiotic factors, as well as lack of willingness by national governments to invest in agricultural research and development. This results into significant yield reductions of about 30-100%, leading to acute food insecurity and economic losses worth of millions of dollars (VIB, 2017; IPBO, 2017; FAO, 2017; Macauley and Ramadjita, 2015; ASARECA, 2014).

PESTS AND DISEASES

Biotic factors are serious threats to maize production in SSA. Insects/pests of maize include aphids, weevils, mites, fall armyworm, mice and rats and are very destructive to maize production in the region (Ong'amo et al., 2016; Louie, 1980). Fall armyworm, reported in West Africa in 2016, is currently the most destructive insect to maize and many other cereals and is spreading fast across SSA (Prasanna et al., 2018). Details of common insects and pests of economic importance in maize are given below (Appendix 1). Major diseases of maize in Africa include maize lethal necrosis (MLN), maize chlorotic mottle virus (MCMV), sugarcane mosaic virus (SCMV), maize streak virus (MSV), *Turcicum* leaf blight (TLB), gray leaf spot (GLS), common rust, aflatoxin and downy mildews; which cause significant yield losses (Appendix 2). Perpetuation of both pathogens and pests in SSA is encouraged by the ideal tropical temperatures and relative humidity (Ramadjita, 2015; Sharma and Misra, 2011). Since diseases and pests occurrence is dependent on climatic conditions, it is difficult for farmers to provide effective control measures. For example, during high rainfall seasons diseases are more pronounced compared to seasons with less rains (Xia et al., 2016; Kiruwa et al., 2016; Sibiya et al., 2013). Major among the diseases of maize is MLN which has recently emerged as the most deadly in east and central Africa with yield loss of 100% in severe cases (ASARECA, 2014; Kiruwa et al., 2016; Isabirye and Rwomushana, 2016). It was first reported in Kenya (2011), then quickly spread to many countries including Uganda, Tanzania, Rwanda, DR Congo, Burundi, Ethiopia and similar symptoms reported in South Sudan (Adams et al., 2014; Lukanda, 2014; Mahuku et al., 2015; Wangai et al., 2012). The disease results from co-infection of maize plant by MCMV transmitted by thrip, and any member of the potyviridae especially SCMV transmitted by aphid (Mbega et al., 2016; Gowda et al., 2015). Although a lot of research is ongoing to counteract the disease, no resistant maize variety for MLN currently available to farmers in Africa.

LOW SOIL FERTILITY AND LAND DEGRADATION

Loss of soil fertility and soil degradation are common phenomena in SSA. Common causes of land degradation include human population growth, poor soil management, deforestation, insecure land tenure systems, climatic variations and soil types in various agro-ecologies (Detchinli and Sogbedji, 2015). In some parts of SSA such as South Sudan, maize farmers usually practice bush burning, tree cutting and elicit felling for the purposes of land clearence for crop planting, yet farmers do not replant trees as replacement (Bationo et al., 2006; FAO/WFP, 2016). In many cases crops such as maize are planted without intercropping. These practices result into increase in deforestation, land degradation and poor crop yield. In Africa, at least 485 million people are subject to land degradation effects with an annual loss of $9.3 billion (Detchinli and Sogbedji, 2015). The rate of loss of forest land (deforestation) is very high in Africa that within few years forest cover has decreased from 656 to 635 million ha, mainly due to conversion of forest land into agricultural fields (Detchinli and Sogbedji, 2015; Bationo et al., 2006). Similarly, continued weathering and high leaching have resulted into soil acidity (high pH) and aluminum toxicity in many cropping areas in SSA (Sebastian, 2014).

CLIMATIC CHANGES

Maize is highly prone to climatic change effects such as high temperature, drought and heat stress, flooding and unpredictable rain patterns. Majority of maize growers in SSA are subsistence farmers that depend entirely on rainfall (AGRA, 2017). In the last few years, rainfall patterns in SSA have changed drastically (Ammani et al., 2013). Fluctuations in time and amount of rainfall affect maize production as farmers may not be able to plant their crop in time, or the amount of moisture received may not be enough to grow maize in a given season (Masarirambi and Oseni, 2011). Rise in mean temperatures and drought stress favour insects/pests to feed on the crop as source of moisture, leading to serious damages and yield losses (Mwalusepo et al., 2015; Kutywayo et al., 2013). For example, insects such as fall armyworm and stem borer have been reported to inflict more damages on maize when there is a dry spell, especially during the vegetative stage (Prasanna et al., 2018; OCHA, 2017; Sebastian, 2014; Sibiya et al., 2013).

LACK OF ACCESS TO IMPROVED TECHNOLOGIES

Annual maize production in the region remains below optimum because of a variety of factors such as low levels of fertilizer application, use of unimproved maize varieties and unimproved agronomic practices (Sebastian, 2014). This has impacted heavily on maize productivity, consequently, SSA imports 7×10^6 tonnes per year which is about 28% of the annual demand (AGRA, 2017; Isabirye and Rwomushana, 2016; ASARECA, 2014).

LACK OF NATIONAL INVESTMENT IN RESEARCH AND DEVELOPMENT

Low national investment in agriculture is another setback that has greatly affected maize production in SSA (Pardey et al., 2016). Majority of the countries in the region (including South Sudan) do not meet the Comprehensive Africa Agriculture Development Program (CAADP) goal which commits each country to contribute 10% of its GDP to agriculture development annually (Karugia et al., 2014; Kimenyi et al., 2012). As a result, the region is failing to fulfill the long-term commitments to investments in research and development (R&D) and associated educational and science-based regulatory capabilities, which are vital for strengthening local innovation and institutional capacities required for improvement of agricultural productivity (Pardey et al., 2016; Sebastian, 2014).

POOR POLICY

Other factors such as small-sized and family-owned farm, lack of credit, labor, and physical capital; limited education, information, infrastructure and markets; weak land tenure arrangements; and political instability are contributing significantly to low maize yield in SSA (AGRA, 2017; Deininger et al., 2017; Pardey et al., 2016; Ruth et al., 2012; HLPE, 2011). Consequently, food shortages have persisted in many parts of the region where food reserves sometimes fall below the critical levels. As a result, famines, poverty and food insecurity are wide spread with poverty level being the highest in the world (Burchi et al., 2016; FAO, 2016; Smith et al., 2006). Adoption of GMO technologies could significantly enhance average maize yield (kg/ha) in farmer fields in SSA. However, due to poor agricultural policies, majority of governments in SSA still regards experimentation and adoption of GMO crops as a taboo (AGRA, 2017). Breeding of many crops including maize is mainly funded by international donors however; many institutions do not have linkages with these multi donors, making it difficult to access research funding. Majority of the population in

SSA are smallholder farmers occupying the rural areas (Melusi et al., 2016). Due to poor systems of governance and lack of democracy, rural areas can turn into political grounds leading to displacement of farmers from their farmlands, resulting into little or even no cultivation at all.

CONCLUSION

Maize is in the centre of food security and agricultural sustainability in SSA however, its production is constraint by complex factors including pests, disease, low soil fertility, climate changes, and inadequate knowledge about the crop. As a result, average grain yield (t/ha) in SSA remains below the world's average. Although extensive efforts have been committed towards maize improvement in Africa, a lot yet need to be done including better understanding of the crop. The compendium generated here could provide useful insights into tropical maize and might contribute towards better management of the crop for enhanced food security in Sub-Saharan Africa.

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Conflict of interest

The authors declare that there are no potential conflict(s) of interest(s).

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Appendix 1. List of common insects and pests that cause diseases and disorders in maize in Africa and other parts of the world.

Phylum	Order	Family	Species	Common name	Impact/damage	Geographic distribution	Yield losses (%)	Reference
Arthropoda	Trombidiformes	Tetranychidae	*Tetranycusurticae*	Two-spotted spider mite	May cause excessive leaf damage hence reduction in yield	USA and Europe	47	PIONEER, 2018; Peairs, 2014; Fasulo, 2009
Arthropoda	Coleoptera	Tenebrionidae	*Gonocephatum* spp.; *Plerohelaeus* spp.	False wireworm	Attacks germinating seeds and shoots, feeds on dry seed under dry conditions.	Europe, Australia, USA	70	Saussure et al., 2015; Mcdonald, 1995
Arthropoda	Coleoptera	Elateridae	*Elateridaess*spp.	Wireworm	Feeds on underground stem and on seed	Worldwide	10-80	Furlan et al., 2017; Barsics et al. 2013
Arthropoda	Coleoptera	Scarabidae	*Holotrichia* spp.	White grubs	Feed on plant roots, plant appears stunted, wilted, discolored, or dead, or cause germination failure.	Worldwide	40-80	Teshita and Gashaw, 2014; Tippannavar, 2013; Cherman et al., 2013
Arthropoda	Coleoptera	Scarabaeidae	*Heteronychusarator*	African black beetle	Chews into stem of young plant and kills the growing point.	Africa, South America, Oceania	20-30	Abdallah et al., 2016; Ekman, 2015
Arthropoda	Coleoptera	Gurculionidae	*Sitophilus zeamais*	Maize weevil	Lays eggs in maturing grain, feeds on grains up to storage	Worldwide	5-90	Nwosu, 2018; Khakata et al., 2018; Suleiman, 2016; Zunjare et al., 2015
Arthropoda	Coleoptera	Diniderinae	*Prostephanustruncatus*	Larger grain borer	Adults and larvae feed on germ and endosperm reducing grain quality. Adults and larvae also burrow through grain	Africa, North America, South America and Mediterranean	9-45	Ndiso et al., 2017; Suleiman, 2016; Popoola et al., 2015
Angiosperms	Asterids	Orobanchaceae	*Striga* spp.	Striga	The weed penetrates roots and feeds on nutrients from the plant (parasite), leading to poor growth and death.	Worldwide	12-100	Suleiman, 2016; Mbogo et al., 2016; Kim et al., 2002
Arthropoda	Coleoptera	Cicadellidae	*Cicadulina* spp.	Maize leafhopper	Feeds on maize plant and injects toxin and transmits maize streak virus, also causes 'wallaby ear' disease.	Africa and the surrounding islands	1-100	Karavina, 2014; Martin and Shepherd, 2009; Alegbejo et al., 2002
Euathropoda	Lepidoptera	Noctuidae	Cutworm	Cutworm	Feeds on young leaves and stems.	Many parts of the world	10-75	Charleston, 2013; Cullen and Jykotika, 2008
Arthropoda	Thysanoptera	Thripidae	*Frankliniella williamsi*	Maize thrips	Found in whorls, tassels, ears, leaf underside. Attacks at ear formation, transmits MCMV provide entry points for infection by *Fusarium spp.*	Many parts of the world	7-94	Sappington et al., 2018; Deng et al., 2014; Nelson et al., 2011; Parsons and Munkvold, 2010; Scheets, 1998; Nault et al., 1978
Arthropoda	Hemiptera	Aphididae	*Rhopalosiphum maidis*	Corn aphid	Transmits SCMV and maize dwarf mosaic virus	Worldwide	10-45	Sappington et al., 2018; Marie-Jeanne et al., 2011; Louie, 1980
Euathropoda	Lepidoptera	Noctuidae	*Helicoverpa*spp.	Corn earworm	Attacks during tasselling and silking, leading to poor pollination and seed set, and provide entry points for fungal diseases.	Worldwide	7-15	Uddin et al., 2009; Cook and Weinzieri, 2004
Euathropoda	Lepidoptera	Noctuidae	*Spodoptera frugiperda*	Fall armyworm	Feeds on leaves and may cause severe defoliation at silking leading to yield reduction.	Americas, African and some parts of the world.	17-100	Prasanna et al., 2018; Romero Sueldo et al., 2010; Hruska and Gould, 1997

Appendix 1. Contd.

Euathropoda	Lepidoptera	Noctuidae	*Busseola fusca*	Maize stalk borer	Tunnels into stems of young plants causing central leaves to wither.	Africa	10-100	Ong'amo et al., 2016; Cobellis et al., 2007; De Grooote, 2002; Moyal, 1998
Euathropoda	Lepidoptera	Crambidae	*Chillo partellus*	Spotted stalk borer	Feeds on all parts of maize plant except the roots.	Asia and Africa	40-80	Nabeel et al., 2018; Mwalusepo et al., 2015; Ullah et al., 2010; Mgoo et al., 2006
Chordata	Psittaciformes, Passeriformes, Galliformes	Psittaculidae, Corvidae, Numididae	Birds	Sparrow, Crows and ravens, Guineafowl, Red-winged blackbird, Brown-headed cowbird, Common grackle, Blackbirds	Birds consume grains during or after planting, damage germinating grains, open husks of ears and feed on mature grains.	Worldwide	3-40	Telenko et al., 2018; Canavelli et al., 2014; Kale et al., 2012
Chordata	Rodentia	Muridae, Thryonomyidae	*Mus* spp., *Rattus* spp., *Thryonomys* spp.	Mice, Rats, Cane rats (grasscutter)	Rodents eat newly sown seed and chew on stems of young plants, or dry grains. Grasscutters damage maize plants by chews on the stems.	Mice and rats are worldwide, grass cutters are only found in Sub-Saharan Africa.	11-100	Ognakossan et al., 2018; Swanepoel et al., 2017; Mulungu, 2017; Avenant et al., 2016; Suleiman and Rosentrater, 2015; Aluko et al., 2015; Mdangi et al., 2013; Makundi et al., 1991
Chordata	Rodentia	Sciuridae	Squirrels	Squirrels	Eat grains during or after planting, chews on stems of young plants, eat mature grains	Worldwide	10-57	Gurnell et al., 2009; Devault et al., 2007; Signorile and Evans, 2007; MacGowan et al., 2006; Key, 1990
Chordata	Primates	Cercopithecidae	Primate	Savannah monkeys, Long-tailed macaque, Chimpanzee, Blue monkey, Baboon	Damage maize cobs while still green, especially at milking stage.	Many parts of the world	50-80	Ango et al., 2017; Gobosho et al., 2015; Mc Guinness and Taylor, 2014; Wallace and Hill, 2012; Naughton-Treves et al., 1998

Appendix 2. Common diseases of maize, geographical distribution and their economic impacts.

Kingdom	Family	Species	Disease/common name	Impact/damage	Geographical distribution	Yield loses	Reference
Bacteria	Enterobacteriaceae	*Erwinia* spp.	Bacterial stalk rot	Upper stalk rots with slimy, smelly, mushy tissues and stalk falls over. Early infections cause rotted leaves in the whorl prior to tasselling.	Worldwide	21-99	Kumar et al., 2017; Thind and Payak, 1985; Thind and Payak, 1978
Fungi	Nectriaceae	*Fusarium* spp.	Fusarium cob/stalk rot	Poor root development of seedlings, mature plant shows rotten tissues and falls down easily, white fungal growth covers kernels or entire cob and toxins produced by the fungus may cause health issues.	Worldwide	10-50	Madege et al., 2018; Gai et al. 2018; Beukes et al., 2017; Kenganal et al., 2017; Ncube et al., 2011; Mueller et al., 2016; Cook, 1978
Fungi	Trichocomaceae	*Aspergillus* spp.	Aflatoxin	Different species produce mycotoxins that cause ear rot after harvest, moulds growth in store, favoured by high temperature, high humidity and stress during grain maturation. The toxins are poisonous to both animals and humans.	Worldwide	30-40	Suleiman and Rosentrater, 2015; Karthikeyan et al., 2013; Hell et al., 2008
Fungi	Pleosporaceae	*Exserohilum turcicum*	Turcicum leaf blight	Greyish-green, water-soaked spots which may cover most of leaf area, reducing the photosynthetic area.	Worldwide	13-70	Debela et al., 2017; Liu et al., 2017; Mueller et al., 2016; Nwanosike et al., 2015; Ali and Yan, 2012; Vivek et al., 2010
Fungi	Pleosporaceae	*Cochiobolus heterotropus*	Southern corn leaf blight	Brown spots on leaves, also causes kernel rot.	Worldwide	15-100	Bruns, 2017; Mubeen et al., 2017; Anon, n.d.; Ali and Yan, 2012; Zwonitzer et al., 2009
Fungi	Pleosporaceae	*Cochiobolus lunatus*	Curvularia leaf spot	Causes seedling blight and germination failure.	Worldwide	10-60	Gao et al., 2015; Akinbode et al., 2014
Fungi	Mycosphaerellaceae	*Cercosporazeae-maydis and Cercospora zeina*	Gray leaf spot	Grey lesions develop on maize leaves, affecting leaf photosynthetic area.	Worldwide	5-100	Dhami et al., 2015; Ali and Yan, 2012; Crous et al., 2006; Ward et al., 1999
Fungi	Pucciniaceae	*Puccinia sorghi*	Common rust	Pustules form on leaves with mass of red-brown powdery spores.	Worldwide	12-61	Ali and Yan, 2012; Dey et al., 2015; Groth et al., 1983; Vivek et al., 2010; Wang et al., 2014; Yang et al., 2017)
Fungi	Pucciniaceae	*Puccinia polysora*	Southern corn rust	Pustules are produced in abundance after infecting the exposed leaves and sheaths of susceptible plants, leading to widespread death of the infected corn tissue, severe desiccation of the plant, and early senescence.	Worldwide	20-80	Bruns, 2017; Mubeen et al., 2017; Wanlayaporn et al., 2013; Ali and Yan, 2012; Raid et al., 1987
Fungi	Ustilaginaceae	*Ustilago maydis*	Common smut	The fungus infects the host plant and invades the ovaries, causing the kernels to swell and form tumor-like galls.	Worldwide	20-41	Aydo et al., 2015; Allen et al., 2011
Fungi	Nectriaceae	*Gibberella zeae*	Gibberella stalk rot /pink ear rot	Causes seeding blight, plant may die prematurely, and stalk rots and breaks easily. Ear rot damage can lead to toxin infection which is harmful to livestock and human.	Worldwide	5-20	Mueller et al., 2016; Malvick, 1995
Fungi	Nectriaceae	*Fusarium* spp.	Ear rot	The fungus attacks all stages and all parts of plant, leading to root rot, seedling blight, stalk rot and ear rot.	Worldwide	4-50	Mueller et al., 2016; Gai et al., 2018; Quesada-Ocampo et al., 2016; Hefny et al., 2012; Ako et al., 2003; Sharma et al., 1993
Fungi	Microbotryaceae	*Sphacelotheca reiliana*	Head smut	Black masses of spores replace the ears and/or tassels.	Worldwide	10-100	Li et al., 2015; Flett, 2014; Maina and Kirubi, 2010

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Oomycetes	Sclerosporaceae	*Peronosclerospora* spp.	Downy mildew	Stunted, yellow, thickened leaves, tassels usually do not develop or show abnormal development (crazy top).	Worldwide	20-100	Sireesha and Velazhahan, 2016; Lukman et al., 2013; Trivedi et al., 2006; Amusa and Iken, 2004
Oomycetes	Pythiaceae	*Pythium* spp.	Pythium	Seedling disease where seedling may not emerge or may turns yellow after emergence and die (dumping off disease), leading to poor stand. It can also affect plant at reproductive stage	Worldwide, moist environments	Up to 60	Reyes-Tena et al., 2018; Zhang and Yang, 2000
Virus	Unassigned	Maize lethal necrosis	Combination of maze chlorotic virus and a member Potyviridae	Plant shows chlorosis, mosaic and yellowing of leaves, followed by plant death due to the synergistic interaction of MDMV and MCMV co-infection.	East and Central Africa	0-100	Mahuku et al., 2015; Wangai et al., 2012
Virus	Tombusviridae	Maze chlorotic mottle virus	Maize chlorotic mottle	Infected plants show leaf mosaic with fine, chlorotic and longitudinal yellow streaks seen parallel to the leaf veins. The streaks may coalesce to create chlorotic mottling, followed by leaf necrosis, stunting and plant death.	East Africa and parts of the world	7-94	Nelson et al., 2011; Scheets, 1998; Nault et al., 1978
Virus	Potyviridae	Sugarcane mosaic virus	Sugarcane mosaic	Maize plants infected with SCMV show mosaic symptoms (irregular distribution of green islands on the leaf surface) including stunting, chlorosis, and reduction in plant weight and grain yield. Infections at early growth stage may lead to complete failure in grain formation	Worldwide	10-45	Marie-Jeanne et al., 2011; Louie, 1980
Virus	Potyviridae	Wheat streak mosaic virus	Wheat streak mosaic	Affected plant manifests yellow and green striped leaves, and stunting. It is severe on wheat but can combine with MCMV and cause MLN in maize.	Worldwide	Negligible	Mar et al., 2013; Murray et al., 2005
Virus	Potyviridae	Maize dwarf mosaic virus	Maize dwarf mosaic	Light and dark-green mosaic, ring spot or yellowing of leaves. Transmitted by aphids.	Worldwide	0-90	Goldberg and Brakke, 1987
Virus	Unassigned	Maize rough dwarf virus	Maize rough dwarf disease	Infected plant shows severe stunting with book-shaped stem, and enation on leaves, leading to poor flowering and ear formation.	Worldwide	10-70	Dovas et al., 2004
Virus	Geminiviridae	Maize streak virus	Maize streak disease	Infected maize plants show streak disease initially manifests as minute, pale, circular spots on the lowest exposed portion of the youngest leaves.	Africa, the islands of the adjacent Indian ocean, India and southeast Asia	1-100	Marie-Jeanne et al., 2011; Martin et al., 2009; Alegbejo et al., 2002; Wambugu and Wafula, 1999; Bosque-Pérez and Buddenhagen, 1999