INFLUENCE OF PLANTING DEPTH AND INTRA ROW SPACING ON GROWTH, SEED TUBER YIELD AND QUALITY OF POTATO AT HOLETTA CONDITION, CENTRAL HIGHLANDS OF ETHIOPIA

By

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JUNE, 2016

JIMMA UNIVERSITY, ETHIOPIA

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DEDICATION

This thesis is dedicated to the late my beloved mother **Zewudinesh Teferi** and my Father **Negash Adera** who passed away without seeing my success in academic career. May their gentle and loving soul rest in peace.The dedication also extends to my younger brother, **Nunu Negash**, for his life and wellness saved from sever car turn over accident with the help of almighty GOD during my study period.

STATEMENT OF AUTHOR

I declare that this piece of work is my own and all sources of materials used for this thesis work have been duly acknowledged. The thesis has been submitted in partial fulfillment of the requirements for the Degree of Master of Science at Jimma University College Agriculture and Veterinary Medicine and is reserved at the University Library to be made available to users. I solemnly declare that this thesis work is not submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate.

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Name: Kasaye Negash

Place: Jimma, Ethiopia

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Date of submission_______________

BIOGRAPHICAL SKETCH

The author, Kasaye Negash Adera, was born on January 19, 1983 at Kimbibit Woreda, North Shewa Zone of Oromia Regional State. He attended his elementary school in Sombo Primary School, his junior secondary education in Kotu Elementary and Junior Secondary School and his secondary school in Hailemariam Mamo Comprehensive Secondary School at Debrebrihan and in Sheno Senior Secondary School at Sheno town of North Shewa Zone. After completion of his high school education, he joined Jimma University College of Agriculture and Veterinary Medicine in December 2002 and graduated with BSc degree in Horticulture in July, 2006.

After graduation, he joined, Oromia Zone of Amhara Regional State, Urban Administrative office of Kemise Town where he worked as representative head of Agriculture sector for eight months. In July, 2007, he was employed by Ethiopian Institute of Agricultural Research (EIAR), Holetta Agricultural Research Center (HARC) where he served as Junior to Assistant Researcher on Agronomy/ Breeding of Potato Research Program until he joined Graduate Study Program of Jimma University College of Agriculture and Veterinary Medicine in 2013/014 academic calendar to pursue a graduate study leading to a Master of Science Degree in Horticulture (Vegetable Science).

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ABBREVIATIONS AND ACRONYMS

AGRISNET	Agriculture Information System Network
CIP	International Potato Center
CSA	Central Statics Authority
EARO	Ethiopian Agricultural Research Organization
FAOSTAT	Food and Agricultural Organization Statics Division
HARC	Holetta Agricultural Research Center
MoARD	Ministry of Agriculture and Rural Development

TABLE OF CONTENTS

Contents **Pages**

TABLE OF CONTENTS (*CONTINUED*)

TABLE OF CONTENTS (*CONTINUED*)

LIST OF TABLES

Contents **Pages**

LIST OF TABLES *(CONTINUED)*

LIST OF TABLES IN THE APPENDIX

Contents **Pages**

INFLUENCE OF PLANTING DEPTH AND INTRAROW SPACING ON GROWTH, SEED TUBER YIELD AND QUALITY OF POTATO (*Solanum tuberosum* L.) AT HOLETTA CONDITION, CENTRAL HIGHLANDS OF ETHIOPIA

ABSTRACT

Planting depth and intra row spacing are among the important agronomic practices in potato seed production. However, farmers in Ethiopia often use haphazard planting depth and intra row spacing, which contributes to the low yield. Thus, the study was conducted to assess the effect of planting depth and intra row spacing on growth, seed tuber yield and quality of potato under Holetta condition, during 2015 off growing season. Four levels planting depth (12cm, 15cm, 18cm and 21cm) and intra row spacing (15cm, 20cm, 25cm and 30cm) were combined in 4x4 factorial arrangements and laid out in randomized complete block design with three replications. Data were collected on growth, seed tuber yield and physical quality parameters and analyzed using SAS Version 9.0 statistical software. Results revealed that both the main and interaction effect of planting depth and intra row spacing significantly (P< 0.05) influenced most parameters studied except for main stem number, specific gravity and dry matter content. Deeper planting (21cm) delayed emergence, flowering and physiological maturity by about 6.16, 8.76 and 8.08 days, respectively, and plant height decreased by 3.67cm compared to planting depth of 12cm. Similarly, heaviest average tuber weight and high number of large sized tubers were gained from depth of 21cm while depth of 18cm resulted in higher a verge tuber yield. Plants grown at intra row space of 30cm took significantly longest days to flower and physiological maturity and the shortest in plant height than those grown intra row spacing of 15cm. The average tuber yield per hill, average tuber weight, large sized tuber number and yield produced at intra row spacing of 30cm is significantly (P<0.05) higher than those obtained from intra row spacing of 15cn by 33.37,23.16,47.64 and 36.67 %, respectively. The interaction of 18cm x30cm depth and intra row spacing resulted in highest average number of tubers while combination of closer intra row (15cm) with deeper (21cm) and shallow depth (12cm) resulted in the lowest one. The highest number and yield of total and marketable tuber number and yield were harvested at the interaction of 18cm x 15cm depth. Whereas, the lowest marketable number and yield of tubers was obtained from the shallow depth (12cm) combined with wider intra row spacing (30cm). Similarly, potato planted at 18cm x15cm depth and intra row spacing resulted in maximum number and yield of under, small and medium sized tubers. In conclusion, most studied yield and quality parameters of the tested variety had superior response to interaction effect of 18cm x 15cm, 15cmx15cm and 18x20cm depth and intra row spacing. Therefore, planting depth of 15cm and 18cm combined with intra row of 15and 20cm can be used as preliminary information for further investigation of high marketable and better quality seed tuber yield. However, the present study was done only for one season at one location; it would be advisable to repeat the experiment for more number of years and locations to come up with comprehensive recommendations.

Kay words: Marketable tuber, Parameters, Tuber number, Tuber weight and tuber size

1. INTRODUCTION

Potato (*Solanum tuberosum* L.) is the world's fourth major crop after rice, wheat and maize in terms of yield which counts for about 45% of the total world production of all tuber crops and eighth in terms of area under cultivation (FAO, 2007). It is one of the most productive and widely grown food crops in the world forming a basic food and source of primary income for many societies (FAO, 2010; Gebremedhin *et al.*, 2013). The potential of high yield, early maturity, relatively stable yield under conditions in which other crops may fail and excellent food value give potato great potential for improving food security, increasing household income and reducing poverty (FAO, 2010; Gebremedhin *et al.*,2013; Devauxe *et al.*, 2014). It was also reported that the annual productions of potato in the world is about 376 million metric tons from 19, 337,100 hectare and in Africa about 30,498,600 tons from 2,045,990 hectares while in Ethiopia total production is around 775,503 tons from 69,999 hectares of total area coverage (FAOSTAT, 2014).

Nutritionally potato was reported as cheap source of energy due to its large content of carbohydrate. Beside, this potato contains high quality protein (lysine) and holds significant amount of vitamin B, C and minerals. Since potato contains all necessary nutrients, it supports life better than any other crop when eaten as the sole article of diet (Khan *et al.*, 2010; Nunn and Qian, 2011).

It was reported that potato was introduced to Ethiopia by a German Botanist Schimper in 1858 (Pankhurst, 1964; Horton, 1987). Since then, potato gradually holds great promise for improving the livelihood of millions of smallholder farmers in the highlands of the country (Gebremedhin *et al.*, 2013). It became the one among the most economically important crops as a source of food and cash in the country (Gildemacher *et al.*, 2009; Adane *et al.*, 2010). Its genotypic variation and relatively short vegetative period allows farmers to find an appropriate season for its cultivation under a wide range of weather patterns and less predictable climates. As a result, the combined area planted to potato in Ethiopia for both *Belg* (February to May) and *Meher* (from June to October) growing seasons is about 179,000 hectares (CSA, 2014a).

More than 70% of the available agricultural land in Ethiopia is suitable for potato production which is located at an altitude of 1500 to 3000 meter above sea level with an annual rainfall between 600 and 1200 mm (Gebremedhin *et al.,* 2008a). In spite of suitability of the land for production and its popularity, the productivity of potato is relatively low, which is about nine tons ha^{-1} (CSA, 2014a). The prominent factors influencing the low yield of the crop include drought (Doss *et al*., 2008; FAO, 2010) shortage of good quality seed, lack of appropriate agronomic practices, low use of inputs (Lung`aho *et al.,* 2007; Medhin *et al.,* 2008), disease and pests (Bekele and Eshetu, 2008; Habtamu *et al.,* 2012), improper time of harvesting, storage and marketing facilities (Tekalign, 2005; Gebremedhin *et al*., 2013).

In order to alleviate some of the problems the national potato research program has been made a considerable progress in relation to development of varieties, agronomic and seed production techniques and integrated pest management (IPM) for major diseases and insect pests in different agro-ecological zones of the country (Gebremedhin *et al.*,2012). As result, with almost 35 years of CIP‘s technological support through Ethiopia has been able to release more than 31 improved varieties (MoARD, 2013). Among the released varieties Jalene, Gudene, Guassa, Gera and Belete are the most widely grown at present (Gebremedhin, 2013). A participatory potato technology development, dissemination and the use of farmer based seed (informal seed) tuber production were undertaken mainly in the central highlands of Ethiopia since 1998 in collaboration with different stake holders (Gebremedhin *et al.,* 2008b). Hence, the knowledge of participating farmers on production and management of relatively healthy seed potato production has been improved and they become the main source of improved potato seed tubers in the country (Gebremedhin *et al.*, 2012).

According to Abebe *et al. (*2013) the majority of potato growing smallholder farmers still use low yielding local seed due to limited access to quality seed tubers. Seed tuber quality which is characterized by tuber size, physical characteristics, physiological age and seed tuber health is usually the most expensive single input to potato cultivation accounting for 40 to 50% of production cost (Gathungu *et al.,* 2015). As the final quality and quantity of potato seed tuber yield is determined by the quality of the potato seed tuber, shortage of it is recognized as the most important factor inhibiting potato production (Gebremedhin *et al.*, 2012). Thus, application of appropriate production practices which start from selecting best production site, appropriate agronomic practices and timely application of production inputs such as nutrients, water and crop protection measures are important in achieving quality seed of potato production (Pehrson *et al.,* 2010).

Thus, optimizing of planting depth and intra row spacing of the plant is among major agronomic practice which needs more attention for seed potato production. As the economical part of potato is produced underground, early development of below ground morphology, tuber expansion, yield and tuber quality are among major aspects affected by planting depth (Pavek and Thornton, 2009). According to Chehaibi *et al. (*2013) report shallow planting is preferred in wet and heavy soils because in such soils deep planting of the tubers may lead to exhaustion of stored food before the sprouts emerge above the soil. Conversely, they also stated that in light textured soils, where there is a risk of dehydration due to moisture stress, deep planting is essential. Lambion *et al.* (2006) advocated that deep planting may also limit the damage to tubers by certain pests especially potato tuber mouth.

Plant density is also the main management area for seed potato tuber production because of its effect on the seed cost, plant development, yield and quality of the crop (Bussan *et al.,* 2007). The seed potato yield can be maximized at higher plant population (closer spacing) or by regulating the number of stems per unit area (O'Brien and Allen, 2009). Rahemi *et al*. (2005) also reported that the 20-cm intra-row spacing showed 36.39% increase in yield in comparison with 30cm spacing. Recent research conducted in Tigray indicated that intra-row space of 20 cm increased total number of tubers and tuber weight per plant (Harnet *et al.,* 2014). Although report of Berga *et al.* (1994) indicated that intra row spacing for seed tuber production as 20cm, it was not much practical since the practice in seed potato production is not clearly different from ware potato production for the case of planting depth and intra row spacing. According to EARO (2004) 30cm intra row and 75cm inter row spacing with 10-15cm planting depth used for all varieties released so far in Ethiopia and serve as standard recommendation in the area of potato production for ware or seed.

However, it was reported that agronomic practices of seed potato is different from ware potatoes since the production in seed potato targetes for high multiplication rate, high number of seed sized tubers and maintenance of healthy seed tubers that have optimum physiological quality (Lung'aho *et al.,* 2007). Therefore, the depth and intra row spacing levels that may lead to optimum yield of ware potato may not be suitable for seed tubers yield or vice versa. Both local and improved varieties of potato that all grown in Ethiopia may differ in response of planting depth and intra row spacing to get maximum yield of seed tubers. However, there is no updated recommended depth and intra row spacing for seed tuber production concerned the recent potato variety under production and the season of growing. Hence, due to lack of adequate information on variety, area and purpose specific depth and intra row spacing, most potato producers in Ethiopia in general and the central high lands in particular use the same depth and intra row spacing, regardless of the purpose of planting either for ware or seed tubers. Therefore, the current study was initiated with the following objectives:

- **General objective**

  - ✓ To determine the effect of planting depth and intra row spacing on seed potato tuber yield and physical quality under Holetta condition, central highlands of Ethiopia.

- **Specific objective**

  - ✓ To determine the optimum depth and intra row spacing of potato for optimum good quality seed tubers.

2. LITERATURE REVIEW

2.1. The Potato Crop

Cultivated potato (*Solanum tuberosum* L.) is a highly heterozygous tetraploid (4x = 48), belonging to the *Solanaceae* family together with other crops like tomato and pepper. It is an annual dicotyledonous, when grown for botanical seed, but is treated as a perennial because of the vegetative propagation from tuber for commercial purpose (Mosley *et al.,* 2000). It has pinnately compound pattern alternate leaves on its above ground stem and specialized underground storage stems or tubers (Decoteau, 2005).

Potato has five distinct growth stages such as, sprout development, vegetative growth, tuberization (tuber formation), and tuber bulking and tuber maturation. Timing of these growth stages varies depending upon environmental factors, such as elevation and temperature, soil type, availability of moisture, cultivar selected, geographic location and agronomic practices (Khan *et al.,* 2011).It has an indeterminate growth pattern and produces a fibrous adventitious root system. This develops just above the nodes on underground portion of the stem (Dwelle and Love, 2003).

Potato tubers are actually a modified stem with approximately 70 -75% content of water and a remaining 25-30% of dry mater. They have nodes or eyes from which the new growth begins and the new growing stems from each eye are called sprouts. Sprouts grow from the tuber after a period of dormancy after they are harvested which varies largely between cultivars. After the dormancy is broken, sprouts grow, and when planted, they give rise to the plant stems from which all the vegetative part of the plant are grown. Underground, lateral shoots called stolons are formed from which the new tubers were formed (Mosley *et al.,* 2000).The main stem of the potato plant terminates in a flower cluster. Flower bud abortion may occur at a very early stage of development but in any case apical growth of the main stem ceases with formation of the flower buds (Alemkinders and Struik, 1994).

Potatoes are mainly propagated by vegetative methods (cloning) and the primary commercial propagation methods. Vegetative reproduction ensures a uniform crop, opposing to what would happen with sexual propagation. Sexual propagation of potato is accomplished by planting its true seed; but a high variability exist between this seed and that is why it is not commonly used. However, sexual seed is becoming more and more popular; especially for breeding purpose and in places where disease pressure is very high to maintain disease free seed (Mosley *et al.,* 2000).

2.2. Importance of Potato

Among the root and tuber crops, potato ranks first followed by cassava, sweet potatoes and yams in terms of the number of producer countries (FAO, 2008). It is the third highest yielding crop on the basis of fresh matter, after sugarcane and sugar beet (Khan *et al.,* 2010). Potato is an important crop and it can supplement the food requirements of the country in a considerable way as it produces more dry-matter food, proportionate protein, and produces more calories from unit area of land and time than other main food crops (Pandey, 2007). Since potato contains all important vitamins and nutrients, it supports life better than any other crop when eaten as the sole article of diet (Khan *et al.,* 2010; Nunn and Qian, 2011).

Potatoes also provided indirect benefits. Being relatively easy to store, potatoes provided excellent fodder for livestock (primarily pigs and cattle). This meant that potatoes also increased meat consumption, as well as manure, which was a valuable input for crop production (Nunn and Qian, 2011). Its shorter growing period makes it possible for the small scale farmer to use this crop in a system where more than one crop is possible on the same land per season (Schott *et al.,* 2000). It is mainly produced to overcome the transitory food shortage that occurs during rainy season. It is considered as transitional crop as it enables farmers survive the hunger months (Stevenson *et al.,* 2001).

Potato is a very important food and cash crop in Ethiopia, especially in the highland and mid altitude areas (Gebremedihin *et al.,* 2008a). It serves as food and cash crop for small scale farmers, occupies the largest area compared to other vegetable crops and produces more food per unit area and time compared to cereal crops (Yigzaw *et al.,* 2008). As a food crop, it has a great potential to supply high quality food within a relatively short period and is one of the cheapest sources of energy. Moreover, the protein from potato is of good composition with regard to essential amino acids in human nutrition (Berga *et al.,* 1994).

Potato has also a promising prospect in improving the quality of the basic diet in both rural and urban areas of the country. Apart from consumption of boiled potatoes; it is now extensively used in the wide arrays of traditional stew preparations in both rural and urban areas. In this regard, potato is supplementing and substituting pulse crops that are commonly used for these purposes. Potato consumption has expanded to include chips, crisps and mixture preparations with other vegetables which are becoming popular in urban areas in recent years (Gebremedhin *et al.*, 2008b; Gildemacher *et al.*, 2009; Adane *et al.*, 2010).

2.3. Ecological and Cultural Requirements of Potato

Ethiopia has an estimated seventy percent of arable land potentially suitable to potato cultivation (Gebremedhin *et al.*, 2013). Most of this land is contained in the Central Highlands, at altitudes ranging from 1,500 - 3,000 meters above sea level (m.a.s.l) and annual precipitation of 600 - 1,200 millimeters (mm) (Medhin *et. al.* 2001).The highland areas of Ethiopia (1,500 m.a.s.l) where generally well suited for seed potato production.

The agricultural calendar of Ethiopia is regionally variable due to great diversity of agro ecology. Potatoes are generally planted to correspond to the peak of the *meher* long rains. In frost-free areas, another crop might be planted several months later to utilize the end of *meher* rains and any residual moisture. Where irrigation is feasible, an additional crop can be planted in February or March, usually past the danger of frost in most of Ethiopia (Tesfaye *et al* 2008). Where late blight has become a serious constraint to potato production, some farmers have shifted production to the *belg* season, especially where irrigation is available (Medhin *et al*., 2001).

Temperature and photoperiod have marked effect on the production of a successful potato crop. Tuberization is also favored by long-days of high light intensity. Potato production largely depends upon night temperature, with highest production at 10-14 ^{0}c night temperature, but no tuberization occurs if night temperature is 20 ^{0}c and above. For sprouting and initial growth of potato it needs temperature of 18-20 ^{0}c. The young plants grow best at a temperature of 24 ^{0}C. Late growth is favored at a temperature of 18 ^{0}C. Tuber production is the maximum at 18-20 ^{0}c, and decrease with rise in temperature. At about 30 ^{0}C the tuber production is totally stop. At higher temperature the respiration rate increases, and carbohydrate produced by photosynthesis are consumed and never stored in tuber. High temperature at any growing period affects the size of leaflets, thereby reducing the tuber formation (Rai and Yadu, 2005).

Potato can be grown in all types of soil except saline (alkaline) and heavy water-logged clays soils. Loamy soil; sandy loamy soil; and organic matter enriched soils are the most suitable for cultivation of potato crop. Optimum yield of potato need a well-drained loamy or sandy loam, relatively free from stones. Better tuber yields have been obtained from potatoes grown at soil pH (H_2O) of 5.0 to 7.0 (AGRISNET, 2010).

Very shallow planting of seed tubers may result in inadequate soil moisture around the seed piece and greening caused by exposure to light. On the other hand, planting too deep will slow tubers to emerge and may subject to attack by various diseases. As a result, planting ought to be deeper on lighter soils than on heavy soils (Wilson *et al.,* 2010).

2.4. Tuber Bulking of Potato

Tuber bulking results from two basic processes, tuber initiation and tuber growth. Timing and duration depend upon geographic location, environmental factors, and cultivar. Tuber initiation occurs at about 20 to 30 days or more (up to 45 days under long day conditions) after plant emergence and last for a period of 10 to 14 days. The potential tuber number that can be successfully produced by a plant varies with the genotype (most cultivars having a consistent number of tubers on each stem), physiological age of seed, number of stems per hill (stem population) and environmental conditions during initiation phase of growth. Environmental conditions affecting tuber initiation include planting date, early season temperature, nutrition and water management, and weather extremes such as hot climate, hail or frost (Kleinkopf *et al.,* 2003; Mihovilovich *et al.,* 2009).

Although many tubers may be initiated during the first four to six weeks of growth, only a fraction of these tubers actually achieves commercial size (greater than 30 mm diameter) (Levy and Veilleux, 2007). After initiation, both the weight and volume of the tubers increase almost linearly, a process referred to as tuber bulking (Levy and Veilleux, 2007). Tuber growth can last from 60 to over 90 days and tuber enlargement which takes place during this phase continues as photosynthates are translocated from the vines to the tubers (Mihovilovich *et al.,* 2009).

The duration and rate of tuber bulking vary among cultivars and depend on environmental conditions (Levy and Veilleux, 2007; Mihovilovich *et al.,* 2009). Bulking rate is greater under short days and moderate temperatures. These conditions favour dry matter partitioning to the tuber, promote tuber growth and restrict haulm growth. Long days and higher temperatures favour dry matter partitioning to the haulm, promote haulm and root growth and delay tuber growth. Tuber bulking restricts shoot and root growth, acting as an alternative and strong sink for plant resources (Levy and Veilleux, 2007).

2.5. Potato production Status in the World, Africa and Ethiopia

Potato is grown in more than 150 countries and consumed almost daily by more than billions of people (FAO, 2008). However, until the early 1990s, most potatoes were grown and consumed in Europe, North America and countries of the former Soviet Union.

According to FAOSTAT (2014) the world potato production was raised to 376,453,000 tons from area coverage of 19,337,100 ha. The report also indicated that Asia was the leading area coverage (9,892,470 ha) followed by Europe (5,725,560 ha), Africa (2,045,990.00 ha), Latin America (959,404 ha) and North America (567,875 ha) with production of 187,219,000; 114,295,000; 30,498,600; 15,621,180 and 24,465,019 tons, respectively. However the productivity was high in North America (43.08 ton ha^{-1}) and least in Africa (14.91).

Lately, there has been a dramatic increase in potato production and demand in Asia, Africa and Latin America, where output rose from less than 30 million tons in the early 1960s to more than 165 million tons in 2007. China is now the biggest potato producer, and almost a third of all potatoes are harvested in China (FAO, 2010).

Following the introduction of the potato in Ethiopia, it was gradually adopted by the farmers (Kidane-Mariam, 1980). The first available potatoes were probably of a very limited genetic base, hence, vulnerable to diseases and pests, and were limited to the colder highlands until wider adoption of the potato occurred at the end of the nineteenth century in response to a prolonged famine (Gebremedihin *et al.,* 2001).

Potato production has increased considerably through the twentieth century in Ethiopia. In 1975, the area of cultivation was estimated at 30,000 ha, with an average yield of approximately five tons per hectare (Gebremedihin *et al.,* 2001). However, potato cultivation declined in the early 1980s, due in part, to widespread infestation of late blight, *Phytophthora infestans*. Starting from 1991, potato production has resumed its increasing trend.

Gebremedihin *et al*. (2001), reported that the area of potato in Ethiopia was 50,000 ha by the mid 1980's and 160,000 ha in the early 2001s; with average yields around eight tons per hectare. An upward trend in potato production might be partly due to the continuing increase in population and subsequent decline in the average size of farm holdings, hence, pressure for agriculture to become more labor intensive. Ethiopia is the 11th top potato producing country in Africa (FAOSTAT, 2006).

According to (CSA, 2014b) the highest production of potato in Ethiopia is in the northwest, central, south and south east with sufficient moisture, favorable day to night temperature regimes, and irrigation facilities. More than 3.3 million smallholders are engaged in potato production and over 1.61 million tones of potato were produced in 2013/14, a 71% increase compared to production in 2008/09. The total area allocated to potato also expanded by over 9% from 0.16 million hectares in 2008/09 to 0.18 million in 2013/14. Similarly, average potato yield exhibited a 57% growth from 5.7 ton/ha in 2008/09 to 9.0 ton/ha in 2013/14 (CSA, 2014b). The adoption and coverage of 25.2% of the total potato area in the country with improved varieties have partly contributed for the witnessed productivity gain (Labarta *et al*., 2012).

2.6. Potato Seed Tuber Production Practice in Ethiopia

Seed potato quality is a key factor, and the most important ingredient for successful potato production (Lacha *et al.,* 2013). According to Van de haar (2013) commercial setting of a private sector seems to be a prerequisite for a sustainable seed system resulting in a permanent supply of high quality seeds.

In all areas of Ethiopia, mostly potato tubers are sorted into ware and seed types immediately after harvest. For most potato producers seed potato is usually considered as the by-product of ware potato (Gebremedhin *et al*., 2013). Only some farmers in the central and north-western areas of Ethiopia have recognized the problems of using part of ware potato as planting material, such as disease transmission which results in yield loss. According to Adane *et al*. (2010) and Tewedros (2014) reported in the central and north-western areas, some farmers practice positive selection (selecting the best and save the seed for next season growth) and some also grow seed potatoes on a separate piece of fertile gentile land.

A survey by Adane *et al*. (2010) showed that 13% of the farmers in the district of Degem and 15% of the farmers in the district of Jeldu in the central area and 8% of the farmers in the district of Banja in the north-western area produced seed potatoes sort out from ware potatoes whereas only 1% of the farmers in district of Degem, 14% of the farmers in the district of Jeldu and 6% of the farmers in the district of Banja produced seed potatoes separately.

In the central and northwestern areas of Ethiopia, 9% of farmer's were found to produce seed potatoes through positive selection and 2% of the farmers were found to produce seed potatoes on separate plots (Gildemacher *et al.,* 2009). Seed tubers supplied by the informal seed potato system (supplies 98.7% of seed tubers used in the country) were deemed to be inappropriate in size, poor in health, unsuitable in physiological age (premature or over mature), poor in genetic quality, impure (varietal mix-up),and physically damaged. Besides, in the informal seed potato system, seed tubers are produced usually as part of ware and stored under poor conditions (Adane *et al.,* 2010).

The most common potato spacing in Ethiopia for ware potato production is 30cm x75cm intra and inter row spacing, respectively. However, the same spacing is commonly used by farmers and researchers as well for seed tuber production. On the other hand, farmers in Ethiopia often use even closer spacing than national recommended (30x75cm) for both ware and seed potatoes production (Mulatu *et al.,* 2005).

2.7. Response of Potato Growth Parameters to Planting Depth and Spacing

2.7.1. Days to emergence, flowering and physiological maturity

Planting depth determines the time and energy the sprout requires to emerge, thereby early establishment and vigor are affected which are vital in seed potato production. For instance, deep planting result in delayed emergence and ground cover (Struik and Wiersema, 1999). In contrary, shallow planting restricted rapid sprout emergence by less soil moisture content (Chehaibi *et al.,* 2013). It was also reported that, more stem can be produced from pieces of seed planted at shallow depth due to shallow planting allows the pieces of seed to be exposed to warmer soil temperatures than deeper planted seed pieces (Pavek and Thornton, 2009).

The depth of planting potato seedling derived from true potato seed had significant effect on days required for 80% emergence, plant height and crop coverage. Deeper depth of planting tended to increase the days required for 80% emergence. Among the tested four depths of planting deeper depth (7.5cm) took the maximum days for emergence while the shortest time was required for surface planting to complete 80% emergence as potato sprouts had to come across long distance of the ground to emerge in deep planting than shallow planted tubers (Sultana *et al.,* 2001).

Pavek and Thornton (2009) also reported that emergence rate accelerated at shallow planting than deeper planting. Similarly Bohl and Love (2005) and Chehaibi *et al.,* (2013) reported that crop emergence was delayed as planting depth increased more slowly for their roots grow best laterally at depth and make the most of available water and nutrients for the crops.

Potato needs to get enough intra and inter row spacing to allow maximum tillering of the plant for an optimum number and better quality tuber formation. The risks associated with the improper planting way are increased incidence of disease problems, slow emergence, in efficient land utilization and low canopy development (Khan *et al.*, 2011). Inter and intra row spacing and their interaction had significant effect on the emergence and successful seedling growth for both seed and ware potatoes. Potato seedlings require wider spacing for better and early emergence, maturity as well as for most of the growth variables (Bikila *et al.,* 2014a). However, indefinite increases in spacing between plants and rows do not result in further change in these variables' rather result in prolonged days to flowering and maturity (Tesfaye *et al.,* 2012)

According to Bikila *et al.(*2014a) combination of inter and intra row spacing of 60x40 cm and70x30 cm took longer days (16 days) for emergence and treatment combination 70x20 cm, 75x30 cm, 75x40 cm, 80x30 cm and 85x40 cm on the other hand emerged within 12 days after planting. From their findings they suggested that seedlings emerged at relatively faster rate in a wider spacing as compared to spacing contained greater number of plants per plot. He farther recommended that for proper emergence and growth of potato for both seed and ware an inter row spacing of 70-75cm and intra row spacing of 20-30 cm are the best combinations for potato seedling emergence and establishment provided that tubers meant for seed and ware are planted separately in space or time

According to Tesfaye *et al. (*2012) intra row spacing had significant effect on growth parameters of potato including days to 50% flowering and maturity, plant height except main stem number. The earliest days to flowering was resulted at the closer intra row spacing of 10cm and 20cm, whereas, days to 50% flowering was prolonged in 30 and 40 cm intra row spacing .Wider intra row spacing delayed days to 50% flowering by three days as compared to the closest intra row spacing of 10cm. Days to 50% flowering were prolonged for plants grown with wider intra row spacing (Law-Ogbomo and Egharevba, 2009)

The research conducted in north Shewa zone (Tesfaye *et al*., 2012) indicated that the earliest days to 50% maturity (106.91 days) were observed at the closer intra row spacing of 10 cm but it was extended (113.33 days) at the wider intra row spacing of 40 cm .Plant maturity was delayed in the wider intra row spacing as compared to the closest intra row spacing as a result of intense inter plant competition at the closer intra row spacing that could lead to probably depletion of the available nutrients and hence, plants stressed tend to senesce earlier. Increasing planting density had shortened days to maturity (Mengistu and Yamoah, 2010; Tesfaye *et al*., 2012)

At the treatment combination of inter and intra row spacing of 70x30 cm and 75x20 cm potatoes matured earlier (81 days) as compared to potatoes planted at treatment combination of 80x40 cm and 85x40 cm which took 91 days. As the number of plants per unit area is reduced by increasing the inter and intra row spacing there is a chance of availability of nutrients, light and space that plants may find to grow more vegetative which extends maturity time (Bikila *et al.,*2014a). Mengistu and Yamoah (2010) also reported that increasing plant density fastened days to maturity

2.7.2. Plant height

Sultana *et al.,* (2001) report indicated that the height of potato seedling derived from true potato seed at 7.5 cm depth is higher compared to shallow (2.5cm) planted at its maximum vegetative growth or stage. According to their finding report the highest percentage of crop coverage was also observed at maximum depth of planting i.e. 7.5cm while the lowest was at surface planting

According to Bikila *et al.* (2014a) the tallest (82.66 cm) and relatively shorter (57.33 cm) plant height was resulted from 80x40cm and 60x30cm inter and intra row spacing combination, respectively. The widest spacing enhanced growth and height of the plant than narrow spacing probably due to better availability of nutrients, water and sun light. Moreover plants in wider spacing have less competition and grow more number of shoots, while densely populated plants showed intensive competition which might lead to a decrease in plant height (Zamil *et al.,* 2010).

In contrary, Tesfaye *et al. (*2012) reported the highest (66.1 cm) and lowest (62 cm) plant height at closer (10cm) and wider (30 and 40 cm) intra row spacing, respectively. Vander Zaag *et al.* (1989) also indicated that plant height was initially similar in all treatments but after 72 days those closely spaced became taller. As intra row spacing increased plant height decreased linearly but closer intra row spacing (higher plant density) resulted in the highest plant height (Zebarth *et al.,* 2006; Law-Ogbomo and Egharevba, 2009).The contrasting reports by different Authors are due the climatologically and soil fertility variation.

2.7.3. Stem number

A number of potato stems arise from each tuber because each tuber has a number of “eyes”, which give rise to a stem. Potato stems can be either a main stem, which grows directly from a seed tuber, or a secondary stem if it branches off the stem. The potato stem system forms part of the stolons and tubers. Plants grown from tubers have more main stems than those derived from true seed. Each stem from a single eye can be regarded as an independent production unit. The general crop performance, harvestable yield and tuber size are strongly influenced by stem number per hectare (Shayanowako *et al.,* 2015).

Shayanowako *et al. (*2015) reported that planting depth influenced the number of emerging stems per tuber. They also explained that a suitable planting method ensures survival and emergence of all sprouts developing from a seed tuber. The effects of planting depth on stem density (number) have been directly or indirectly investigated by a number of researchers (Stalham *et al.,* 2001; Bohl and Love, 2005; Pavek and Thornton, 2009) who reported contrasting results.

Potato stem numbers were reduced as planting depth increased. Beside this, below and above ground morphological responses to planting depth have been observed different (Bohl and Love, 2005).However, the number of tubers, stolons and nodes per stem increased with an increase in planting depth (Pavek and Thornton, 2009). Some report indicated that depth of planting had no significant effect on the number of main stem per hill due to the development of main stems depend on number of eyes in a seed piece (Sultana *et al.,* 2001).

The two components of potato crop density are plant density and number of stems per plant or hill. Stem density influences number of tubers, size of tubers, and multiplication rate which is determined by the number of main stems that emerge and survive (Gulluoglu and Arıoglu, 2009). Zabihi *et al.(*2010) reported that the highest stem numbers being produced at wider plant spacing and lowest at the highest density plantings and further stated as in row spacing had effect on the number of main stem per unit area. Planting of different sized seed tubers at various in row spacing resulted in different number of main stems. Small seeds had the highest stem density at closet in row spacing, while the large seeds had the similar stem density at the widest in row spacing (Gulluoglu and Arıoglu, 2009; Zabihi *et al.,* 2010).

However, Sturz *et al.* (2003) reported as plant spacing had no effect on the number of main stems or branches per plant due to number of stems were increased as a result of either planting smaller tuber size or more tuber number per unit area. It was also explained as the number of stems is function of seed pieces type as their production were not affected by plant density and the trait is much influenced by the inheritance of the potato crop (Mulubrhan, 2004; Zelalem *et al.,* 2009).

2.8. Effects of Planting Depth and Spacing on Potato Yield Parameters

2.8.1. Number and average tuber weight

The number of tubers set by plants determined by stem density and spatial arrangement of the tubers (Endale and Gebremedhin, 2001). The number of tubers produced per seed tuber will be reduced when higher plant populations are used. Any increase in stem density over the commercial range results in a reduction in number of tubers set per stem. The total number of tubers per unit area increased linearly with increasing density. Spacing affects the number of tubers per plant and increased at wider spacing (Gulluoglu and Arrogilu, 2009).

Research report indicated that, the highest and the lowest number of tubers per plant was obtained at 30cm and 20cm intra row spacing, respectively. Hence, the increase in-row spacing led to significant increase in number of tubers per plant (Sanlı *et al.,* 2015). In contrary, increasing plant density lead to decrease in the number of tuber per plant due to per share of the light and food are reduced resulting in increased competition within plants (Sanlı *et al.,* 2015). Tuber production per plant are directly correlated with number of main stems per plant and significantly affected by inter-plant and intra plant competition (Bussan *et al.,* 2007). The highest total number of tubers per hill was recorded at low plant density whereas lowest number of tuber per hill was obtained at high plant density (Frezegi, 2007). Many Authors recently also reported that tubers number per plant increased with the increasing distance between the in-rows of plants (Jamaati *et al.,* 2010; Tahmorespour *et al.,* 2013; Ayupov *et al.,* 2014).

According to Masarirambi *et al.* (2012) plant population density significantly affected tuber numbers, with the highest density (90 by 15 cm) plants having a lower number of tubers per plant while the lower density (90 by 45 cm), resulted in highest number of tubers per plant. Space availability has an imposing effect on number of tubers formed. The greater the space, the higher the number of tubers formed per plant (Gulluoglu andArioglu, 2009).

Increase in plant density resulted in increase in number of tubers per meter square due to increase in number of stolon and stem density (Khalafalla, 2001). The highest number of tubers per meter square was found from closer spaced plants (Zabihi *et al.,* 2010; Masarirambi *et al.,* 2012).

Inter and intra row spacing had very highly significantly affected total number of tuber per hectare. Harnet *et al. (*2014) reported maximum total number of tubers per hectare at 65cm inter row and 20cm intra row spacing while the lowest number of tubers per hectare was at 80cm inter row and 35cm intra row spacing. Similarly, Bikila *et al. (*2014b) reported greatest number of tubers per hectare from 60cm x 20cm spaced plants while the lowest ones from 70cm x 40cm inter and intra row combination.

Tuber weight which was mainly measured in gram depends not only on the operating time of the leaf canopy but also on the conditions of operation and conditions of root growth (Snapp and Kravchenko, 2010).The lowest mean tuber weight was obtained from the closest in-row spacing (20 cm) and mean tuber weight values tended to increase with widening in-row spacing. Similarly, many authors stated that the crop established at closest planting produced low average tuber weight than that established at wider planting (Jamaati *et al.,* 2010; Masarirambi *et al.,* 2012; Tahmorespour *et al.*, 2013). Dehdar Masjedlo (2002) also reported that increasing plant density increased tuber yield, number of main stems and the average number of tubers per meter square but the average tuber weight was reduced.

Zabihi *et al.* (2010) explained that increase in density probably causes the increase in competition between and within plants and hence, leads to decrease in availability of nutrients to each plant and consequently, results in decline of mean tuber weight. Others reported that increasing planting density lead to a decrease in the average weight of the tuber and an increase the outcome of the amount and weight of the tubers per unit area (Gasimova *et al.*, 2010; Jamaati *et al.,* 2010; Zabihi *et al.,* 2010). It was also reported higher average tuber weight at wider plant spacing as compared to closer plant spacing (Bussan *et al.,* 2007; Gulluoglu and Arroglu, 2009; Harnet *et al.*, 2014).

2.8.2. Seed tuber yield

Since, the economical part of the crop, potato tuber; is produced underground, planting depth highly influence potato tuber production. The development of below ground morphology, tuber expansion, yield and tuber quality are among the aspects affected by planting depth (Pavek and Thornton, 2009).

According to Chehaibi *et al*. (2013) experiment conducted using two levels of planting depth of 10cm and 15cm with two varieties show that both produced the highest tuber yields at 15 cm depth compared to those planted at depth of 10 cm. This implied that planting deeper allows the crop to get more food reserves and water encouraging development and increasing fresh weight of tubers. Moreover, increasing planting depth resulted with, higher number of nodes, stolon and tuber number while shallow planting hastened potato plant emergence in which the early emergence not always results in increased number of tubers or higher final yield per entire plant (Pavek and Thornton, 2009).

By contrast, at shallow planting, plant biomass was relatively less developed, leading to a lower tuber yield. Studies of Abdulla *et al*. (1993) and Bohl and Love (2005) showed that potato yields increased when planting depth increased up to the optimum. Pavek and Thornton (2009) showed, in a study on the effects of planting depth, the performance of two commercial varieties of potatoes were lower for the reduced depth. Other, authors, reported about tuber yield as no significant difference between different planting depths (Singh, 1985; Kim, 1989; Sultana *et al.,* 2001)

The most appropriate planting density of potato is that in which each unit area have the greatest assimilation surface, at the same time the plants are under adequate lighting and the leaves maintains vital functions as long as possible (Kotikiv, 2011).The wider planting distance in rows resulted in highest and lowest tuber yield per plant and per hectare, respectively (Gulluoglu and Arıoglu, 2009). Increasing planting density lead to a decrease in the average weight of the tuber and an increase the outcome of the amount and weight of the tubers per unit area (Jamaati *et al.,* 2010; Zabihi *et al.,* 2010)

Research result reported from different area revealed that tuber yield of potato is significantly influenced by plant population density or spacing. According to Berga *et al*. (1994), spacing should depend on the intended use of the crop such as for seed or ware. Closer intra-row spacing of 10 or 20cm in rows 75cm apart would be beneficial for seed. Wider intra-row spacing (30 or 40cm) were better, on rows 75cm apart, for ware potato. The amount of seed tuber required and type of output and synergy with other cultural practices, 60 cm inter row spacing, was recommended for seed potato production. However, 75-cm inter-row spacing was found to be optimum and recommended practices for ware potato production at Adet and its environment (Tesfaye *et al.*, 2008).

Bikila *et al.* (2014b) reported maximum yields (933 g) per plant, from 85x40 cm inter and intra row spacing whiles the lowest amount of yield (408 g) from treatment combination of 75 x20 cm resulting to 56% yield difference per plant. In contrary, the highest (38.19 t ha^{-1}) and the lowest (21.22 t ha') total tuber yield per hectare was recorded from inter and intra row spacing combination of 65x20cm and 85x40cm, respectively. This revealed that using wider spacing decreased the yield per hectare but resulted to increased yield per plant. Harnet *et al.* (2014) also reported that the yield of seed tuber per hectare was increased with decreasing plant spacing due to high number of plants per unit area which brings about an increased ground cover that enables more light interception, consequently influencing photosynthesis.

Total yield as well as the average tuber size of potato affected by plant density. Then increasing density resulted in yield increment and average tuber size reduction (Beukema and Van der zaag, 1990). Moreover, closer spacing resulted in more small sized tubers yield (Khalafalla, 2001). Tuber yield affected by plant density as plants planted at wider spacing exhibited highest yield performance compared to those planted at narrow spacing. Significant differences in yield at wider can be attributed to high plant population per plot for plants established at closer spacing compared to lower plant density (Masarirambi *et al*, 2012).

Harnet *et al. (*2014) reported the highest and lowest yield at inter row spacing of 65cm and 80cm.respectively. From their finding, the higher total yield per hectare was obtained from 20 cm intra row spacing and as intra row spacing increased from 20 to 30 cm, total tuber yield decreased by 36% .Decreasing row width below 60 cm could bring in cultural problems in addition to almost doubling the seed rate cost although the problem can be compensated to some extent by using smaller sized tubers. However, problems can be still a challenge for narrow spacing particularly on heavy soils and in high rainfall areas (Endale and Gebremedhin, 2001).

Total yield increases to a maximum with increased stem density and then either remains unchanged with further increase in density or eventually begins to decline. The highest total yield was obtained from the in-row distance of 20 cm and row-width of 75 cm. In a situation where the number of tubers is of greater importance, as in seed production, the narrow row width (20 cm) is to be preferred (Gebremedhin *et al.,* 2008b).

As the planting density increased there was a corresponding increase in yield. Mean total tuber yield was higher at closest in-row spacing (36.70 t/ha) than wider in-row spacing (29.71 t/ha)while the yield per plant significantly decreased as planting distances became closer due to increased inter-plant competition (Sanli *et al.,* 2015). Increase in number of tuber per hectare with increasing plant density may result in increase in tuber yield per unit area. Tuber yield per hectare reduced at wider in-row spacing due to reduction of hill number per unit area. Similarly, with the increased plant density, yield was decreased in each plant but increased per unit area (Bussan *et al.,* 2007; Tahmorespour *et al.,* 2013).

In most of potato producing areas of Ethiopia spacing of 20-30 and 60-75 cm are utilized between plants and between rows, respectively (Agajie *et al.,* 2007). Pavek and Thornton (2009) reported that, tuber expansion is one of the tuber development characteristics most affected by plant density among the other tuber development characteristics. Thus, in addition to competitions imposed by having crops planted near each other, the surrounding soil volume becomes insufficient to hold the expanding masses of tubers

Endale and Gebremedhin (2001) explained that, having optimum number of plants per unit area and spatial arrangements have a great potential in securing high potato tuber yield. They also reported that, practicing appropriate spacing is more important in seed potato production since to secure quality and quantity of the next season potato crop quality and healthy seed tuber is the most determinant in potato production.

Spacing is crucial in determination of appropriate seed rate as far as potato productivity is considered, since low seed rate results in fewer yields, whereas seed rate more than research approved one result in more production cost since it hinders the application and ease of appropriate agronomic practices. Moreover, more seed rate exposes each plant for inter and intra-row nutrient and radiation competition thereby result in less tuber formation per plant (Agajie *et al.,* 2007; Gebremedhin *et al.,* 2008b; Tesfaye *et al.,* 2008).

2.9. Effects of Planting Depth and Spacing on Potato Quality Parameters

2.9.1. Tuber size category

Tuber size is an increasingly important aspect of potato physical quality. Buyers all along the potato market chain from those purchasing seed to end users (fresh market and processing) are requiring a uniform and consistent tuber size profile. The size distribution of harvested crop is one of the factors determining its economic value and specific grades are required for specific market outlets and purposes (Beukema and Van der Zaag, 1990). Most consumers require big size potatoes since large tubers are required for processing, while medium sized tubers are preferred for home consumption and the small once are often used by the farmers for seed and home consumption (Govinden, 2006).

Tubers might be categorized in different way based on diameter of the tubers using calipers or mass of the tubers In most case the categorization based on diameter of are reported as tubers less than 25 mm are under sized (very small), those between 25-35mm are small, 35-55mm are medium and greater than 55 mm are large and tubers which are healthy with a size more than or equal to 25 mm are generally considered as marketable tuber (Hassanpanah *et al.,* 2009; Khan *et al.,* 2011; Abbas *et al.,* 2012).

The effect of population density especially in related to tuber category has been reported in several research reports. Bikila *et.al*.(2014b) reported that increasing the spacing between plants and rows from 60x30cm to 85x40cm resulted to a 53% decreased in number of under sized (<20 mm) potato tubers from 81.66 to 38.66. Similarly, number of small sized tubers (20-30 mm) was also decreased from 86 to 26 as the spacing increased from 60x30 cm to 75x30 cm. While the medium sized tubers (30-40 mm) was considered, relatively higher number (88.33) was found at the narrower spacing of 65x20cm and the lower number (36) was obtained at a spacing combination of 70x30 cm.

The result of recent investigation indicated that the level of intra-row spacing largely affected potato tuber size distribution. Thus, based on market and consumers' demand, it is possible to produce or increase either seed potato or ware potato of required size through the selection of appropriate intra row spacing (Harnet *et al*., 2013). It was also reported that the increase in plant density decreases mean tuber size, due to a reduction in plant nutrient elements, and increase in interspecies competition. However, large number of tubers was produced because of high numbers of stems per unit area (Khajehpour, 2006).

According to Sanli *et al*. (2015) report effect of in-row spacing on tuber size was significantly (P>0.01) important and large sized tuber (>55mm) yield increased with the increase in-row spacing, medium (35-55mm) and small sized (25-35mm) tuber yield decreased. They also suggested that the proportion of larger tuber was the highest at the wider spacing and the non-marketable (under sized tuber) yield increased with increasing stem density due to greater competition for water, nutrients and sunlight during tuber bulking resulting in fewer assimilates available for each individual tuber.

Highest number of small and medium tuber sized potato tuber was recorded at closer plant spacing and the lowest number was obtained at the closet plant spacing. In contrary the highest number of large sized tuber was gained at wider plant spacing (Tesfaye *et al.,* 2013). Undersized and small sized tubers are less desired because of the low market prices (Hossain *et al*., 2011). But, closet spacing increased the number of these undesired potato tubers result to economic loss for the farmers. Medium sized tubers are the most desired ones for their seed value and higher market prices (Bikila *et al.,* 2014b).

2.9.2. Tuber specific gravity and dry matter content

The seed potato tubers produced must present good physiological characteristics such as specific density, starch and dry matter contents which are crucial in improving the vigour of seedlings and tuberization capacity of the resultant plants (Gathungu *et al*., 2015). Potatoes with a high specific gravity have been reported to produce higher yields than potatoes with low specific gravity (USAID, 2011). Studies showed that increasing plant spacing resulted in an increase in specific gravity (Vander Zaag *et al*., 1990; Zebarth *et al*., 2006). Tesfaye *et al.* (2013) attributed this to the resultant less intra-plant competition associated with reduced plant population. White and Sanderson (1983) also showed that wider spacing (38 and 56 cm) increased specific gravity. Shayanowako *et al.* (2014) reported as the lowest specific gravity at highest and lowest stem density while the highest at intermediate stem density.

Specific gravity is highly correlated with dry matter content and the lower tuber specific gravity may result in poorer processing quality such as chips and crisps (Storey and Davies, 1992). Specific gravity of raw potatoes is widely accepted by the potato processing industry as a measure of total solids, starch content and other qualities. It is an indication that the raw potatoes will produce high chip volume due to high dry matter content. Fitzpatrick *et al*. (1964) categorized tuber specific gravity values as low (less than 1.077), intermediate (between 1.077 and 1.086, and high (more than 1.086).

However, Rykbost and Maxwell (1993) reported that plant populations have not an effect on the specific gravity of all the varieties they studied. Moreover, many attempts have been made to correlate variations found in specific gravity of tubers with cultural practices and environmental conditions. Then, variety has been reported by many researchers to be the most important factor determining potato quality (Hegney, 2005; Musa *et al.*, 2007; Abubaker *et al.*, 2011).

Tesfaye *et al*. (2013) found high plant population to be associated with low dry matter content because of high competition for light and other important resources and this then led to a few resources being channeled to each sink. They also reported that the dry matter content rise to a peak at 30cm but then fell with a further increase in plant spacing. The low dry matter content at the widest plant spacing was due to high photosynthetic rate thus a relatively high vegetative growth at the expense of the tubers formation. Similarly, many other studies showed increased dry matter with decreasing plant population (Vander Zaag *et al.,* 1990; Tamiru, 2004; Tafi *et al*., 2010).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

The experiment was conducted at Holetta Agricultural Research Center (HARC), Wolmera District, West Shewa Zone of Oromia Regional State during the off cropping season (from February to June 2015) using supplementary irrigation. HARC is located in Holetta town 29 km west of Addis Ababa, on the way to Ambo. The site is situated at $9^{o}3'00''$ N latitude and 38^{o} 30''E longitude having an elevation of 2400 m a.s.l. The area is characterized by mean annual rainfall of 1100 mm and mean relative humidity of 60.6%. About 70% of the rain falls between June and September and the rest falls between February and April. Potato production is possible in both seasons with rain- fed and using supplementary irrigation. The average annual maximum and minimum temperature is 22.1°C and 6.2°C, respectively. The soil type in the area is predominantly Nitisol which is characterized by having average organic matter (OM) content of 1.8%, Nitrogen 0.17%, phosphorous 4.55ppm and potassium 1.12 Meq/100gm of soil and pH(H_2O) 5.24 (HARC, 2004).

3.2. Experimental Material

Table 1. Morphological and Agronomic characteristics of planting materials

No	Characteristics	Description
1	Variety	Belete (CIP-393371.58)
2	Released year	2009
3	Released Center	Holetta Agricultural Research Center
4	Adaptation	Wide range
5	Resistance	To late blight
6	Growth habit	Semi erect
7	Average number of stems hill^{-1}	Five
8	Average numbers of tubers hill^{-1}	14
9	Plant height	76cm
10	Days to maturity	110-120 days
11	Tuber Yield	47.19 t/ha on research field
12	Altitude	1600-2800 m.a.s.l
13	Rain fall(mm)	750-1000mm

Source: MoARD (2009)

The improved potato variety namely, Belete obtained from Holetta Agricultural Research Center was used for the experiment (Table 1). The variety is cultivated widely and has been highly demanded by farmers due to its high yielding ability, consumer's preference and relatively resistance to late blight as compared to local and other improved varieties (Gebremedhin *et al*., 2013).

3.3. Treatments and Experimental Design

The treatment had two factors in which factor one having four levels of planting depth (12cm, 15cm, 18cm and 21cm) and factor two with four levels of intra row plant spacing (15cm, 20cm, 25cm and 30cm). It was combined in 4x4 factorial arrangements in Randomized Complete Block Design (RCBD) with three replications (Table 2).The total observation had 2736 plants. The field layout was made accordingly and each treatment was assigned randomly to the experimental units within each block.

Table 2.Treatment combinations, number of plants per plot and plant density per meter square.

Treatment	Planting depth (cm)	Intra row spacing (cm)	No of plants ($plot^{-1}$)	Plant density (m^{-2})	Plant density (ha^{-1})
1	12	15	80	8.89	88888.89
2	12	20	60	6.67	66666.67
3	12	25	48	5.33	53333.33
4	12	30	40	4.44	44444.44
5	15	15	80	8.89	88888.89
6	15	20	60	6.67	66666.67
7	15	25	48	5.33	53333.33
8	15	30	40	4.44	44444.44
9	18	15	80	8.89	88888.89
10	18	20	60	6.67	66666.67
11	18	25	48	5.33	53333.33
12	18	30	40	4.44	44444.44
13	21	15	80	8.89	88888.89
14	21	20	60	6.67	66666.67
15	21	25	48	5.33	53333.33
16	21	30	40	4.44	44444.44

3.4. Experimental Procedure

The experimental field was ploughed and disked to fine tilth with tractor before planting for ease of emergency of potato. The total area of the experimental field including the distance between plots and block s was 11m width by 64m length which was 704m^2. The whole field was divided into three blocks each containing 16 plots in which blocking was done perpendicular to the slope gradient of the field. The size of each unit plot was 9m^2 (3m width x3m length) in which each of them had four rows or ridges having inter spacing of 75cm.The sixteen treatment combinations were assign ed to each experimental plot and replicated three times; hence total observations were 48. A distance of one meter, between plots within a block and between blocks was maintained. Uniformly sprouted (three to four) medium sized tubers of 35-45 mm in diameter were selected and hand planted in furrow. Tubers, used for planting, were harvested at the same time and stored in diffused light store for eight months.

Fertilizers were applied as per the recommendation of EARO (2004). Accordingly, 110 Kg N and 90 Kg of P_2O_5 ha^{-1} were applied. Nitrogen was applied in the form of Urea (46% N) 165 Kg/ha (split: half at planting and the rest 45 days after planting as side dress) and P_2O_5 in the form of DAP (46% P_20_5 and 18% N) 195 Kg/ha was side dressed at the time of planting. Other management practices such as weeding, cultivation and ridging were practiced as per the recommendation (Gebremedhin *et al.,* 2008) and irrigation was applied conventionally with furrow method at three days interval for one month and then at five days interval until the plant matured.

Harvesting was done by using hand held tools when the leaves of 70% the plants in the plot were turn yellowish and show sign of senescence. Before harvesting dehaulming was conducted seven days a head to enhance tuber maturity, facilitate harvesting and to reduce tuber bruising.

3.5. Data Collection

For the evaluation of effect of planting depth and intra row spacing on potato growth, seed tuber yield and physical quality data were collected for individual response variables from the two harvestable middle rows of each plot at different times based on the nature of parameters.

The yield and physical quality parameters data were taken during harvesting from the two middle rows at net area of (1.5m x 2.4m=3.6m^2) of each plot. After harvesting tubers were graded in to different size based on their diameter using caliper. Each size of tubers was counted and weighed using sensitive balance to be more accurate.

3.5.1. Growth parameters

A) Days to 50% emergence – Days to 50% emergence were recorded by counting the number of days from the date of planting to the date at which about 50% of the plants in a plot emerged out.

B) Days to 50% flowering – Days to flowering was recorded when 50% of the plant population in each plot produced flowers.

C) Days to 50% physiological maturity – Days to physiological maturity was recorded as days from emergence to maturity when the haulms of 50% of the plant population per plot have showed sign of senescence or turn yellowish.

D) Plant height (cm) – plant height was determined by measuring the height of the randomly selected five plants per plot as the distance from the soil surface to the top most growth point of aboveground at full flowering (Zelalem *et al.*, 2009).

E) Number stems (hill^{-1}) – The average number of main stems produced per hill was recorded by counting the main stem s which came out from the seed tuber from five randomly selected plants from each plot at full flowering (Zelalem *et al.*, 2009).

3.5.2. Yield parameters

The number of tubers hill^{-1}, tuber yield hill^{-1}, average tuber weight, average, marketable and unmarketable tuber number m^{-2}, total tuber yield, marketable seed tuber yield and unmarketable tuber yield ton ha^{-1} data were collected at the time of harvesting from the two middle rows at net area of 3.6m^2.

A) Average number of tubers (hill^{-1}) – It was explained as total number of tubers harvested from hills divided by number of plants harvested.

B) Average tuber yield (g hill^{-1})) – Average weight of total tubers harvested from sampled hills/plants was divided by the number of plants.

C) Average tuber weight (g) - It was recorded as the ratio of the weight of tubers per plant/hill to number of tubers per plant/hill which was expressed in grams at harvest.

D) Average number of tubers (m^{-2}) - The total number of tubers harvested from net area was counted.

E) Marketable number of seed tubers (m^{-2}) - At harvesting the tubers harvested from net area was taken from each plot for determination of marketable seed tuber number. In this study marketable tubers include healthy tubers having size categories greater than 25 mm in diameter.

F) Unmarketable number of tubers (m^{-2}) - Among tubers harvested from net area diseased, rotten, insect attacked, deformed and tubers with diameter less than 25mm were separated and counted.

G) Total tuber yield (ton ha^{-1}) - Total tuber yield was recorded as the sum of marketable seed tuber and unmarketable tuber yield

H) Marketable seed tuber yield (ton ha^{-1}) - At harvesting the plants harvested from net area were taken from each plot for determining marketable seed tuber yield. In this study marketable tubers were include healthy tubers having size categories greater than 25 mm in diameter

I).**Unmarketable tuber yield (ton ha^{-1}) -** Diseased, rotten, insect attacked, deformed tuber and tubers with diameter less than 25mm (non-marketable) were weighed and tabulated

3.5.3. Physical quality parameters

Tuber size categories (under sized, small, medium and large), tuber specific gravity and tuber dry matter content was recorded as follows.

A) Tuber size: Tubers from two central rows was graded by size of tubers: <25mm (under sized), 25- 35mm (small) 35-55(medium) and >55mm (large) (Hassanpanah *et al.,* 2009; Khan *et al.,* 2011; Abbas *et al.,* 2012). Tubers in each grade were counted and weighed.

B) Specific gravity of tubers - This was determined using the weight-in-air/weight-in-water method of measuring the specific gravity (Gould, 1995). A sample of 3 kg tubers of all shapes and sizes were randomly taken from each plot. The selected tubers were washed with water. The samples were first weighed in air and then re-weighed suspended in water. The specific gravity was calculated using the following formula.

$$S_g = \frac{w_a}{w_a - w_w}$$

Where, Sg = Specific gravity; Wa = Weight in air (g); Ww = Weight in water (g)

C) Tuber dry matter content (%) - Clean and unpeeled five potato tubers were randomly selected from each plot, chopped into small cubes, mixed thoroughly, and fresh sub-sample of 200g were placed in a paper bag and put in an oven at 70 ^{o}C until a constant dry weight was attained for about 72 hrs. The sub-sample was immediately weighed and recorded as dry weight (Bonierbale *et al.*, 2006). Percent dry matter content for each sub-sample was computed by dividing weight of sample after drying over initial weight of sample times hundred based on the formula described.

$$\text{Dry matter content (\%)} = \frac{\text{Dry weight (g)}}{\text{Fresh weight (g)}} \times 100$$

3.6. Statistical Analysis

The data were checked for normality and meeting of all assumptions of ANOVA. Then, data were subjected to analysis of variance (ANOVA) using the General Linear Model of the SAS statistical package (SAS®, 2002) version 9.00. All significant pairs of treatment means were compared using the Least Significant Difference Test (LSD) at 5% probability level of significance. Correlation analysis was done between selected growth and yield parameters.

4. RESULT AND DISCUSSION

4.1. Growth Parameters

The results obtained in days to 50% emergence, flowering and maturity, plant height and main stem number are presented (Table 3 and Appendix Table 1) and discussed below.

Table 3. Effect of planting depth and intra row spacing on potato growth parameters evaluated under irrigation at HARC in the 2015 off season (February-June).

Planting depth (cm)	Days to 50% emergence	Days to 50% flowering	Days to 50% maturity	Plant height(cm)	Main stem number
12	12.92[c]	58.92[c]	84.17[c]	75.25[a]	4.63[a]
15	13.08[c]	59.83[c]	85.08[c]	73.58[a]	4.33[a]
18	17.92[b]	64.67[b]	89.58[b]	71.75[b]	4.57[a]
21	19.08[a]	67.67[a]	92.25[a]	71.58[b]	4.38[a]
$LSD_{(0.05)}$	0.78	1.26	1.27	1.72	0.57
P-value	<0.0001	<0.0001	<0.0001	0.0003	0.6595
Intra row Spacing(cm)					
15	15.75[a]	61.50[b]	86.42[c]	78.58[a]	4.40[a]
20	15.83[a]	61.83[b]	86.83[bc]	73.17[b]	4.38[a]
25	16.00[a]	63.25[a]	88.08[b]	71.42[c]	4.48[a]
30	15.42[a]	64.50[a]	89.75[a]	69.00[d]	4.65[a]
$LSD_{(0.05)}$	0.78	1.26	1.27	1.72	0.57
P-value	0.4889	<0.0001	<0.001	<0.0001	0.7620
CV (%)	5.93	2.41	1.73	2.82	15.13

Means followed by the same letter within a column are not significantly different (P > 0.05) from each other; LSD= Least significant difference, CV= Coefficient of variation

4.1.1. Days to 50% emergence

The analysis of variance indicated that there was significant ($P<0.05$) variation in days to emergence for the main effect of planting depth. However, the main factor of intra row spacing and the interaction did not influence days to 50 % emergence (Table 3 and Appendix Table 1). The result revealed that planting potato at the depth of 21cm prolonged days to 50%

emergence very highly significantly (P<0.0001) by 19.08 days compared to planting at the depth of 18cm, 15cm and 12cm (Table 3). However, potato grown at depth of 12cm and 15cm emerged with in 12.92 and 13.08 days, respectively after planting. Planting at depth of 21cm was extended the time of 50% emergence by about 6.16, and 1.16 days than the one grown at depth of 12cm and 18cm, respectively. However, there was no significant difference between the two consecutive planting depth of 12cm and 15cm.

It was observed that as planting depth decreased from 21cm to 12cm, the number of days from planting to 50% emergence was shortened. Deeper depth of planting tended to increase the days required for 50% emergence. Among the four depths of planting, 21cm depth required the maximum days for emergence. On the other hand, the shortest time was required to complete 50% emergence at surface planting. Bohl and Love (2005) reported similar result that emergence of crop was delayed as planting depth increased. This might be due to the fact that in case of deep planting, the potato sprouts had to come across a long distance of the ground to emerge compared to the shallow planting.

The result is in agreement with the findings of Pavek and Thornton (2009) who reported that increased planting depth resulted with delayed emergence, higher number of nodes, stolon and number of tubers while shallow planting hastened potato plant emergency. They also suggested that this early emergence not always result in increased number of tubers or higher final yield per entire plant. Similarly, Sultana *et al.* (2001) reported that deeper depth of planting required maximum days for emergence while shallow depth need minimum days for 80% emergence.

4.1.2. Days to 50% flowering

The analysis of variance indicated that days to 50 % flowering was significantly (P<0.05) affected by planting depth and intra row spacing. However, no significant (P>0.05) interaction effect was observed between two main effects of depth and intra row spacing on days to 50 % flowering (Table 3 and Appendix Table 1). Similar to days to emergency, potato planted at depth of 21cm took longer days to 50% flowering (67.67) which was very highly significantly (P<0.0001) longer period than potato planted at the depth of 18cm, 15cm and 12cm which required 64.67, 59.83 and 58.91 days to 50% flowering, respectively. Potato grown at depth of 12cm was flowered earlier (58.91 days) than planting at depth of 18cm and 21cm, in which statistically similar with potato grown at depth of 15cm to reach its flowering stage (Table 3). The observed variation in terms of flowering date could be attributed to the nutrient and moisture availability from the soil to complete their vegetative growth and to commence their reproductive phase by mobilizing assimilates to the sink sites.

Planting of potato at wider intra row spacing significantly delayed days to 50% flowering while planting at narrow intra row spacing resulted in significantly earlier flowering (Table 3). The earliest days to 50% flowering were observed at the closer intra row spacing of 15 cm and 20 cm while, days to 50% flowering was prolonged in 30 cm intra row spacing (Table 3). Days to 50% flowering was delayed by about 7 days in the wider intra row spacing as compared to the closest intra row spacing of 15cm. Present study indicates that, as intra row spacing increased, the number of days to flowering was significantly delayed. This could be due to higher competition of plants for resources in the closer (15cm) intra row spacing that lead them to stress and ultimately the plants flower early.

This result is in agreement with the work of Tesfaye *et al.* (2012) who reported that wider intra row spacing delayed days to 50% flowering by three days as compared to the closest intra row spacing of 10 cm. Similarly, Law-Ogbomosho and Egharevba (2009) reported that, days to 50% flowering were prolonged for plants grown with wider intra row spacing (lower planting density). However, the present finding is in disagreement with the work of Bikila *et al*. (2014a) which was stated as plants grown in a closer spacing may compete for the available light and may remain in a vegetative stage for longer period than plants grown in a wider spacing. The contradiction of the previous work done at western Ethiopia (Bikila *et al.*, 2014a) with current study result might be due to variation soil condition, variety, climate, management and seasons.

4.1.3. Days to 50% maturity

The variance analysis indicated that days to 50% maturity was significantly ($P< 0.05$) affected by the main factors of planting depth and intra row spacing. However, the interaction of the two main factors found to be non significant on this parameter (Table 3 and Appendix Table 1).The longest days to 50% maturity (92.25 days) were recorded from potato planted at depth of 21cm while shortest days to 50% maturity (84.17) were registered from plants grown at relatively shallow depth (12cm) which was statistically at parity with those grown at depth of 15cm (Table 3). This study indicated that potato grown at deeper planting depth of 21cm took very highly significantly ($P<0.0001$) highest days to 50% maturity compared to planting depth of 18cm, 15cm and 12 cm, by about 2.67, 7.17 and 8.08 more days, respectively. Therefore, as planting depth was increased, the trend of time required to reach maturity progressively prolonged. Early maturity in related to the effect of planting depth was observed to be related with early emergence and flowering. This might be due to the fact that deeper planting, matching with the active growth stage of the plant, created favorable soil environment in relation to nutrient availability and enhanced further vegetative growth that extended days to maturity.

The earliest days to 50% maturity (86.42) were observed from potato grown at closer intra row plant spacing (15cm) closely followed by intra row spacing of 20cm which was statistically at parity (Table 3). However, it was prolonged by 80.08 and 89.75 days to reach 50% maturity at intra row spacing of 25 and 30 cm. Days to 50% maturity were delayed by 3.33 days for potatoes grown in the wider intra row spacing (30cm) as compared to the closest intra row spacing of 15 cm. Generally, planting potato at wider intra row spacing (30cm) prolonged days to 50% maturity by about 1.67, 2.92 and 3.33 days than planting it at intra row spacing of 25cm, 20cm and 15cm, respectively. This could be due to the fact that the presence of intense inters plant competition at the closer (15cm) intra row spacing that leads to depletion of the available nutrient, as a result plants stressed and tend to mature earlier.

The result of current study is in agreement with findings of Mengistu and Yamoah (2010) who reported that closer intra row spacing had shortened days to maturity. In the same way, Tesfaye *et al*. (2012) reported that plant maturity was delayed in the wider intra row spacing compared to the closest one due to intense inter plant competition at the closer intra row spacing. Bikila *et al.* (2014) also stated that as the number of plant per unit area is reduced by increasing the inter and intra row spacing there is a chance of availability of nutrients, light and space that led the plants to grow more vegetative which extended maturity.

4.1.4. Plant height

The analysis of variance is shown that plant height was significantly ($P<0.05$) affected by planting depth and intra row spacing. However, the interaction between planting depth and intra row spacing is not significant ($P>0.05$) (Table 3 and Appendix Table 1). Potato planted at the depth of 12cm was resulted in significantly the tallest (75.25cm) plant height which was statistically similar with potato grown at depth of 15cm, while planting at depth of 21cm ended with the shortest (71.58cm) one which was not statistically different from the height (71.75cm) of those planted at depth of 18cm. The height of potato planted at the depth of 12cm was higher by 3.67cm and 3.56 cm than those planted at depth of 21cm and 18cm, respectively. Present study indicated that as the depth of planting increase the height of potato tends to decrease. This might be due to as the tuber planted at shallow depth the emergence was very fast and the plant utilized stored energy and available nutrients for the shoot growth. While deep planting of the tubers may lead to exhaustion of stored food before the sprouts emerge above the soil. Hence, the plant is shorter than the one planted at relatively shallow depth. However, this study is contradict with the findings of Sultana *et al*.(2001) who reported that plant height obtained from deeper depth of planting was found maximum and the lowest height was recorded from surface planting. The variation with present result might be the environment and planting materials used for the experiment.

On the other hand, intra row spacing also resulted to difference in plant height. Plants grown at intra row spacing of 15 cm had the highest plant height (78.58cm) which was higher than the heights of plants grown at intra row spacing of 20 cm, 25 cm, and 30 cm by about 8.33, 8.4 and 15.47%, respectively (Table 3). Similarly, the height of plants grown at intra row spacing of 20 cm exceeded the heights of plants grown at the intra row spacing of 25 cm and 30 cm by about, 6.28 and 12.97%, respectively. Plants grown at wider intra row spacing of 30cm had the shortest (69cm) plant height which was statistically different with height of plants grown at intra row spacing of 25cm. The current study implied that plant height increased at narrow intra row spacing than wider intra row spacing. Significant increase in plant height with decreasing intra row spacing can be attributed to the increased competition between stems for light and photosynthetic light absorptions as already reported by earlier researchers (Irritani *et al.*, 1983; Gulloglu and Argioglu, 2009). In other way, this might be due to plants grown at wider spacing have a chance to obtain sufficient nutrients, moisture and light due to less resource competition and favored more lateral branching growth as compared to plants grown at narrow spacing.

The present work is in line with work of Tesfaye *et al.* (2012) who explained the highest (66.1 cm) and shortest (62 cm) plant height at closer (10cm) and wider (30 and 40 cm) intra row spacing, respectively. Similarly, as intra row spacing increased plant height decreased linearly and closer intra row spacing resulted in the highest plant height (Zebarth *et al.,* 2006; Law-Ogbomo and Egharevba, 2009). However, this result is in disagreement with the result reported by Zamil *et al.* (2010) and Bikila *et al.* (2014a) that plants in wider spacing have less competition and grow more shoots, while, densely populated plants show intensive competition which leads to decrease in plant height. Bikila *et al*. (2014a) also justified their finding as the tallest plants were obtained at wider plant spacing possibly due to better availability of nutrients, water and sun light since plants in wider spacing are subjected to less stiff competition. The contradiction of the two reports with present result might be due variation in experimental materials, soil condition, seasons and the setup of the experiments.

4.1.5. Number of main stems per hill

The main factors of planting depth and intra row spacing and the interaction had no significant ($P > 0.05$) influence on number of main stem hill^{-1} (Table 3 and Appendix Table 1). Statistically no significance difference between different levels of planting depth with number of stems produced (Table 3).Similarly, Sultana *et al.* (2001) report indicated that depth of planting had no significant effect on the number of main stems hill^{-1} due to the development of main stems depend on number of eyes in a seed piece.

The same to planting depth intra row plant spacing had no significant difference between different levels on the number of main stems produced hill^{-1} (Table 3). This might be due to the production of stem number hill^{-1} mainly controlled by seed tuber size, number and age of sprouts and variety rather than planting depth and in row spacing. But this study mainly considered one variety having relatively similar tuber size and three to four number of sprouts with the same physiological age of eight month storage in diffused light store.

Similarly, Endale and Gebremedhin (2008) reported that main stem numbers depend on seed bed conditions, planting method and seed tuber characteristics such as number of eyes or sprouts, size, physiological age and variety. Many research reports indicated that seed factors are by far the most influential as they govern the number of main stems that can emanate from a seed tuber (Gulluoglu and Arıoglu, 2009; Zabihi *et al.,* 2010). It was also reported as stems per plant were not influenced by plant density but by physiological factors resulting from the management of the seed (Masarirambi *et al.,* 2012). Others explained that the number of stems is function of seed pieces type as their production was not affected by plant density and the trait is much influenced by the inheritance of the potato crop (Mulubrhan, 2004; Zelalem *et al.,* 2009).

4.2. Yield Parameters

The results obtained in yield parameters such as number of tubers hill^{-1}, tuber yield hill^{-1}, tuber weight, average, marketable and unmarketable number of tubers m^{-2}, total tuber yield, marketable seed tuber yield, and unmarketable tuber yield (ton ha^{-1}) are presented and discussed below.

4.2.1. Average number of tubers per hill

The analysis of variance showed that the main factor of planting depth and intra row spacing had significant ($P< 0.05$) effect on average number of tubers hill^{-1} and the two main factors also interacted to influence the number of tubers produced hill^{-1} (Table 4 and Appendix Table 2). The highest average number of tubers (9.15 hill^{-1}) were obtained from plants grown at depth of 18cm combined with intra row spacing of 30cm followed by result gained from those planted at depth and intra row combination of 15cm x30cm (Table 4).The lowest average number of tubers (6.05hill^{-1}) were recorded from plants grown at depth and intra row spacing of 21cm x15cm which was statically similar with the result obtained at treatment combination of 12cmx15cm (Table 4). The average number of tubers hill^{-1} gained from plants grown at planting depth of 18cm combined with intra row spacing of 30cm is higher than those obtained from plants grown at depth and intra row combination of 21cm x15 cm and 12x15cm by about 33.88 and 34.20 %, respectively. The result of the study revealed that average number of tubers produced from depth of 18cm combined with each level of intra row plant spacing is higher than the rest of planting depth combination with similar levels of in row spacing (Table 4).

Table 4. Interaction effect of planting depth and intra row plant spacing on number of tubers produced hill^{-1} at HARC under irrigation in the 2015 off season (February-June).

Planting depth(cm)	Intra row spacing (cm)			
	15	20	25	30
12	6.02^{g}	6.75^{f}	7.14^{f}	8.08^{cde}
15	7.65^{e}	7.13^{f}	7.93^{cde}	8.73^{ab}
18	8.41^{bc}	7.90^{ed}	8.28b^{cd}	9.15^{a}
21	6.05^{g}	7.03^{f}	7.75^{e}	8.40^{bc}
$LSD_{(0.05)}$	0.49			
CV (%)	3.99			
P-value	0.0003			

Means followed by the same letters are not significantly different (P > 0.05) from each other; LSD= Least significant difference, CV=Coefficient of variation

Current study indicated that production of average number of tubers hill^{-1} increased as plants grown at wider intra row plant spacing combined with 18cm planting depth and decreased at narrow intra row plant spacing combination with shallow (12cm) or deeper (21cm) planting depth. This might be due to the less number of plants produced at wider intra row plant spacing than plants at closer intra row spacing which led to minimum competition among plants for space and resources and the availability of moisture and nutrients at optimum planting depth promote the active growth period of the plant for higher number stolons production which in turn for more tubers initiation and development. In addition, better exposure of the plant for interception of high radiation might be increased the photosynthetic efficiency of the plant and finally resulted in high average number of tubers hill^{-1}. This result supported by the finding of Sanlı *et al.(*2015) who reported that increasing plant density lead to decrease in the number of tubers per plant due to per share of the light and foods are reduced

The present finding is in agreement with the findings of Tesfaye *et al.* (2012) who reported that high numbers of tubers per plant were obtained in the wider intra row spacing. In the same way (Zamil *et al.*, 2010) also reported that the wider intra row spacing gave the highest number of tubers per hill. In similar experiment Gulluoglu and Arioglu (2009), also reported that number of tubers per plant increased at the wider intra row spacing. Many authors recently described that tubers number per plant increased with the increasing distance between the in-rows of plants (Jamaati *et al.,* 2010; Tahmorespour *et al.,* 2013; Ayupov *et al.,* 2014). But the current finding is contradict with the work of Harnet *et al*. (2014) who stated that maximum total number of tubers per plant at closer plant spacing while the lowest number of tubers per plant at wider plant spacing. This variation might be contributed by different factors such as soil; climate and the variety used for the two experiments are different.

4.2.2 Average tuber yield per hill (g)

The analysis of variance showed that the main factors of planting depth and intra row spacing had significant ($P< 0.05$) influence on mean tuber yield hill^{-1}. However, the two main factors did not interact to affect the mean tuber yield produced hill^{-1} (Table 5 and Appendix Table 3).Plants grown at the depth of 18cm produced high average tuber yield (845.23g hill^{-1}) followed by the average tuber yield obtained from planting depth of 15cm which was statistically similar with result gained from planting depth of 21cm (Table 5). However, plants grown at depth of 12cm produced low average tuber yield (730.78g hill^{-1}) having statistical difference with potato grown at depth of 15cm and 21cm, which yielded 794.04g and 790.32g hill^{-1}, respectively. Potato grown at the depth of 18cm highly significantly (P<001) exceeded in producing mean tubers yield hill^{-1} than those grown at the depth of 12cm, 15cm, and 21cm by about 13.54, 6.05 and 6.5%, respectively.

The present study show that as planting depth increased up to 18cm, the yield of tubers produced hill^{-1} increased to the maximum but beyond 18cm it starts to decline. This might be due to the creation of favorable soil conditions in moisture conservation and nutrients availability at the optimum depth which promote the active growth period of the plant for higher number stolons production which in turn for more tubers initiation and development that increased tuber number that resulted in higher tuber yield hill^{-1}. This result supported by Berga *et al*. (1994) who reported that tuber yield per plant increased up to certain limits but beyond that it started to decline.

Table 5. Effect of planting depth and intra row spacing on average tuber yield (g $hill^{-1}$) at HARC under irrigation in the 2015 off season (February-June).

Treatment	Average tuber yield(g $hill^{-1}$)
Planting depth (cm)	
12	730.78^{c}
15	794.04^{b}
18	845.23^{a}
21	790.32^{b}
$LSD_{(0.05)}$	47.15
P-value	0.0004
Spacing(cm)	
15	610.07^{d}
20	703.06^{c}
25	873.24^{b}
30	974.01^{a}
$LSD_{(0.05)}$	47.15
P-value	<0.0001
CV (%)	7.16

Means followed by the same letter within a column are not significantly different (P > 0.05) from each other; LSD= Least significant difference, CV= Coefficient of variation

In case of intra row plant spacing, plants grown at wider intra row spacing (30cm) produced highest average tuber yield (974.01g $hill^{-1}$) followed by those harvested from intra row plant spacing of 25cm (Table 5). The lowest average tuber yield (610.07g $hill^{-1}$**)** was harvested at closer intra row plant spacing (15cm) which was statistically significant difference with intra row plant spacing of 25cm and 20cm (Table 5). The average tuber yield $hill^{-1}$ obtained from plants grown at wider intra row spacing (30cm) was higher than those grown at intra row spacing of 25, 20 and 15 cm by about 10.35, 27.82 and 37.37 %, respectively.

The current study implied that average tuber yield $hill^{-1}$ increased as potato grown at wider intra row plant spacing and decreased at closer intra row plant spacing. This might be due to the less number of plants produced at wider intra row plant spacing than plants at closer intra row spacing which lead to minimum competition among plants for space and resources. More over the better exposure of plants for high radiation interception that increased the photosynthetic efficiency of the plant and finally resulting in more number of tubers and bulking of them increased average tuber yield hill^{-1}.

The current result is in line with the finding of Gulluoglu and Arioglu (2009) whose work revealed that major yield components; mean tuber weight and tuber yield per plant, significantly decreased as planting distance got closer due to increasing inter-plant competition. In the same way (Zamil *et al.,* 2010) also reported that the wider intra row spacing gave the highest yield of tuber hill^{-1}. In disagreement with finding of Harnet *et al*. (2014) who reported maximum total yield of tuber per plant at closer plant spacing while the lowest yield of tuber per plant at wider plant spacing due to the variation in number of stems. The difference between current and previous study might be due to variation in variety, soil condition and agro ecology of the localities since the former was conducted at Tigray region.

4.2.3. Average tuber weight (g)

Average tuber weight of potato is influenced significantly ($P< 0.05$) by planting depth and intra row plant spacing. However, the two main factors did not interact to influence the average tuber weight (Table 6 and Appendix Table 3). The maximum average tuber weight (107.61g) was recorded for plants grown at depth of 21cm which was statistically similar with the one harvested from crops grown at depth of 12cm due less number of tubers produced at the two levels (Table 6). The minimum average tuber weight (99.94g) was obtained from plants grown at depth of 18cm which was statically similar with the result found from planting depth of 15cm and 12cm (Table 6). Potato grown at deeper depth (21cm) significantly exceeded in producing high average tuber weight than the one grown at the depth of 18cm and 15cm by about 6.6 and 6.16%, respectively.

This study shows that plants grown at depth of 21cm and 12cm gave relatively maximum tuber weight than plants grown at others two depth of planting tested. The average weight of tuber decreased at depth of high number tubers harvested. This might be due to the result of high average tuber yield hill^{-1} was due to production of more number of tubers.

In case of intra row plant spacing, plants grown at 30cm intra row spacing produced high average tuber weight (113.45g) which was not statistically differ from 25cm (Table 6). The lowest average tuber weight (87.19g**)** was harvested at closer intra row plant spacing (15cm) which was statistically significant difference with intra row plant spacing of 25cm and 20cm (Table 6). The average tuber weight increased to 25cm intra row spacing but no significant difference to wider (30cm) intra row spacing.

Table 6. Effect of planting depth and intra row spacing on average tuber weight at HARC under irrigation in the 2015 off season (February-June).

Treatment	Average tuber weight (g)
Planting depth (cm)	
12	103.53^{ab}
15	100.41^{b}
18	99.94^{b}
21	107.00^{a}
$LSD_{(0.05)}$	5.30
P-value	0.0388
Spacing(cm)	
15	87.18^{c}
20	97.82^{b}
25	112.42^{a}
30	113.45^{a}
$LSD_{(0.05)}$	5.30
P-value	<0.0001
CV (%)	6.19

Means followed by the same letter within a column are not significantly different (P > 0.05) from each other; LSD= Least significant difference, CV= Coefficient of variation

The result revealed that the average tuber weight gradually increased as plants grown at wider intra row plant spacing and decreased at closer intra row plant spacing. The production of tubers with high average tuber weight at wider intra row spacing (30 cm) might be due to less number of stems per unit area which result in less competition for resources (nutrient and carbohydrate) between plants during growth and tuber bulking as compared to plants grown at closer intra row (15cm) plant spacing which resulted in large sized tubers. In other word, by increasing density, the yield increase is attributable to more tubers being produced at the closer spacing per unit area and average tuber weight is decreased due to increased inter-plant competition with closer (15cm) intra row spacing.

This result is consistent with Zabihi *et al.* (2010) who reported that increase in density probably causes the increase in competition between and within plants and hence, leads to decrease in availability of nutrients to each plant and consequently, results in decline of mean tuber weight. Higher average tuber weight was produced at wider plant spacing as compared to closer plant spacing (Bussan *et al.,* 2007; Gulluoglu and Arroglu, 2009; Harnet *et al.,* 2014). Others reported as increasing planting density lead to a decrease in the average weight of the tuber and an increase the outcome of the amount and weight of the tubers per unit area (Gasimova *et al.,* 2010; Jamaati *et al.,* 2010; Zabihi *et al.,* 2010). Authors stated that the crop established at closest planting produced low average tuber weight than that established at wider planting due high computation for resources (Jamaati *et al.,* 2010; Masarirambi *et al.,* 2012; Tahmorespour *et al.,* 2013).

4.2.4. Average number of tubers per meter square

The interaction of planting depth and intra row plant spacing significantly ($P < 0.05$) affected the average number of tubers produced per meter square (Table 7 and Appendix Table 2). The highest average number of tubers (74.72 m^{-2}) were recorded from plants grown at depth of 18cm combined with intra row spacing of 15cm followed by the mean number of tubers (67.96m^{-2}) produced from treatment combination of 15cm depth with the same intra row spacing. The lowest mean number of tubers (35.93 m^{-2}) was obtained at planting depth of 21cm combined with intra row spacing of 30 cm which were not statically different from average number of tubers harvested from treatment combination 12cm x30cm, 12cmx25cm and 15cmx30cm depth and intra row spacing (Table 7). The number of tubers gained from potato grown at treatment combination of 18cm depth with 15cm intra row spacing is higher than the mean harvested tubers from treatment combination of 21cm x 30 cm, 12cm x 30cm and 15cm x30 cm by about 51.9, 50.05and 48.07%, respectively. Plants grown at depth and intra row spacing of 15cm x15cm also produced the second highest average number of tubers which exhibited statistically significant difference from average number of tubers gained from treatment combination of 21cm x 15cm and 18cmx20cm (Table 7).

Present study indicates the maximum number of tubers was obtained at closer (15cm) in row plant spacing combined with all level of planting depth than wider intra row (30cm) combination with different levels planting depth. This is might be the compensation effect of closer intra row spaced plants per unit area than the wider intra row spacing in which the high numbers of stem per unit area resulted in higher number of tubers. In the same way presence of high number of plants per unit area which attributed to the production of many stems resulted in high number tubers per meter square. The increased in number of tubers at higher densities might be also due to the ground being covered with green leaves earlier (earlier in the season, light is intercepted and used for assimilation), and fewer lateral branches are being formed and tuber growth starting earlier. Beukema and Van der Zaag (1990) was reported that increased plant population increased tubers number due to more stems per unit area in which tubers being harvested per unit area of land.

Table 7. The interaction effect of planting depth and intra row plant spacing on average number tubers produced m^{-2} at HARC under irrigation in the 2015 off season (February-June).

Planting depth(cm)	Intra row spacing (cm)			
	15	20	25	30
12	53.80^{c}	45.00^{de}	37.69^{i}	37.32^{i}
15	67.96^{b}	47.50^{d}	41.85^{fg}	38.80^{hi}
18	74.72^{a}	52.69^{c}	43.70^{ef}	40.65^{gh}
21	53.80^{c}	46.85^{d}	40.93^{fgh}	35.93^{i}
$LSD_{(0.05)}$	2.92			
CV (%)	3.76			
P-value	<0.0001			

Means followed by the same letters are not significantly different (P > 0.05) from each other; LSD= Least significant difference, CV=Coefficient of variation

The result of present study is similar with the study of Zabihi *et al.* (2010) and Masarirambi *et al.* (2012) who stated that the highest number of tubers per meter square was found from closer spaced plants. Similarly it was reported that the increase in plant density resulted in increase in number of tubers per meter square as a result of increase in number of stolon and stem density (Khalafalla, 2001).In the same way, Harnet *et al.* (2014) and Bikila *et al.* (2014b) also reported that tuber number per hectare increased as the spacing between plants and rows decreased due more number stems per unit area.

4.2.5. Marketable number of seed tubers per meter square

The interaction of planting depth and intra row plant spacing significantly (P <0.05) influenced marketable number of tuber per meter square (Table 8 and Appendix Table 2).The highest marketable number of tubers (57.87 m^{-2}) were obtained in response to planting the tubers at depth 18cm combined with intra row plant spacing of 15cm followed by treatment combination depth and intra row spacing of 15cmx15cm and 21cm x15cm which resulted in 51.57 and 38.61 tubers perimeter square, respectively. However, the lowest marketable tubers (27.04 m^{-2}) were recorded at depth and intra row combination of 12cm by 30cm which were statistically similar to marketable tubers (28.08 m^{-2}) harvested from 12cm x 25cm depth and intra row spacing combination. Plant grown at combination of depth and intra row spacing of 18cm x15cm produced marketable tubers higher than treatment combinations of 15cm x 15cm and 21x 15 cm by about 10.89 and 33.28%, respectively. Similarly, marketable tuber numbers harvested from treatment combination of 15cm x15 cm depth and intra row plant spacing exceeded that of 12 x 25 cm and 15x25cm by about 8.65 and 8.72%, respectively.

Table 8. The interaction effect of planting depth and intra row plant spacing on marketable number of tubers m^{-2} at HARC under irrigation in the 2015 off season (February-June).

Planting depth(cm)	Intra row spacing (cm)			
	15	20	25	30
12	35.37^{de}	30.28^{ghi}	28.80^{ji}	27.04^{j}
15	51.57^{b}	34.26^{ef}	31.11^{ghi}	29.72^{hi}
18	57.87^{a}	37.13^{cd}	34.07^{ef}	32.04^{fgh}
21	38.61^{c}	34.35^{ef}	32.87^{efg}	32.32^{fgh}
$LSD_{(0.05)}$	2.64			
CV (%)	4.58			
P-value	<0.0001			

Means followed by the same letters are not significantly different (P > 0.05) from each other; LSD= Least significant difference, CV=Coefficient of variation

From this study maximum marketable tubers were obtained from closer (15cm) intra row plant spacing combination with most levels planting depth than wider in row spacing with different levels of planting depth. In other way, potato grown at depth of 18cm combined with most level of intra row plant spacing resulted in higher marketable tubers than the rest of depth and intra row combination tested. This might be due to the depth of 18cm had better soil conditions for proper root growth and nutrient absorption that facilitate the above ground part for better growth and development and intra row spacing of 15cm had high stem numbers per unit area which led to produce high number tubers which resulted in more marketable tuber number as advantage of more tubers produced m^{-2}. Beside these, at closer intra row plant spacing due to the presence of high number of plants per unit area, there is a early canopy closure for more light interception and conservation of available moisture by reducing soil temperature around root zone of the plants which result in less loss of water through evaporation. This increased their photosynthetic efficiency for higher photo assimilate production and partition to tubers which finally resulted in more marketable tubers m^{-2}.

This result agrees with the results reported by Harnet *et al*. (2014) that maximum marketable tuber number ha^{-1} was obtained at closer plant spacing whereas the lowest marketable tuber number ha^{-1} was obtained at wider plant spacing. The finding is also similar with the work reported by Bikila *et al*. (2014b) as the spaced between plants and rows decreased tuber number per plant and marketable tubers ha^{-1} were increased due more number of stems per unit area.

4.2.6. Unmarketable number of tubers per meter square

The interaction of the two main factors planting depth and intra row spacing had significantly ($P<0.05$) affected unmarketable number of tubers produced m^{-2} (Table 9 and Appendix Table 2). The highest unmarketable tubers (18.43 m^{-2}) were recorded from potato grown at planting depth of 12cm combined with intra row plant spacing of 15cm which was statistically similar with unmarketable tubers recorded from crops grown at 18cm x 15cm planting depth and intra row spacing. The lowest unmarketable number of tubers (5 m^{-2}) were recorded at combination of deeper depth (21cm) and wider intra row plant spacing (30cm)followed by treatment combination of the same level of depth with 25cm intra row spacing (Table 9). The unmarketable number of tubers obtained from plants grown at treatment of 12cmx15cm depth and intra row spacing exceeded highly significantly ($P<0.01$) those recorded from plants at depth and intra row spacing of 21cmx30cm and 21cmx25cm by about 72.87 and 56.27% respectively.

Table 9. The interaction effect of planting depth and intra row plant spacing on number of unmarketable tubers m^{-2} at HARC under irrigation in the 2015 off season (February-June).

Planting depth (cm)	Intra row spacing (cm)			
	15	20	25	30
12	18.43[a]	14.72[d]	8.89[g]	8.89[g]
15	16.39[ab]	13.24[d]	10.74[f]	9.07[fg]
18	16.85[a]	15.56[b]	9.63[fg]	8.61[g]
21	15.19[b]	12.50[e]	8.06[g]	5.00[h]
$LSD_{(0.05)}$	1.67			
CV (%)	8.25			
P-value	0.0116			

Means followed by the same letters are not significantly different (P > 0.05) from each other; LSD= Least significant difference, CV=Coefficient of variation

According to this study tubers harvested from plants grown at closer intra row spacing (15cm) combined with most levels of planting depth had high unmarketable number of tubers than those gained from crops grown at wider intra row (30cm) combined with various level planting depth tested (Table 9). The reducing of intra row spacing at relatively shallow depth the number of unmarketable tubers increased. This might be due to closer intra row plant spacing had high competition of plants for growth factors due to high number plant per unit area which led to produce high number of under size tubers and at relatively shallow depth most of the produced tubers are exposed to external environment due lack of enough soil volume to cover the expanding tubers then easily attacked by different insects ,thus, the cumulative of under sized and damaged tubers, resulted in higher number of unmarketable tubers than combination of wider intra row spacing with deeper depth.

This study is in line with the results of Frezgi (2007) who reported that at closest spacing significantly higher number of small tubers was produced as the consequence of higher competition between plants which resulted in high number of unmarketable tuber. Tesfaye *et* *al.* (2013) also indicated that at closer plant spacing produced high number of unmarketable tubers than wider plant spacing due high computation for nutrients and photo assimilates

4.2.7. Total tuber yield

Planting depth and intra row plant spacing affected significantly (P< 0.05) total tuber yield and the two factors highly interacted to influence the parameter (Table 10 and Appendix Table 3). The highest total tuber yield (65.35 t ha^{-1}) was obtained for potato grown at depth of 18cm combined with intra row spacing of 15cm and followed by the yield (52.38t/ha) produced from treatment combination of 15cmx15cm depth and intra row spacing. However, the lowest yield (31.25t ha^{-1}) was obtained at planting depth of 12cm combined with intra row spacing of 30cm. The tuber yield obtained at the treatment combination 18cm depth with 15cm intra row spacing higher than total tuber yield harvested from treatment combination of 15cm x 15 cm, 12cm x 30cm and 12cm x25cm by about 18.29, 38.72 and 34.86 %, respectively (Table 10).

Table 10. Interaction effect of planting depth and intra row plant spacing on total tuber yield (t ha^{-1}) at HARC under irrigation in the 2015 off season (February-June).

Planting depth(cm)	Intra row spacing (cm)			
	15	20	25	30
12	47.42^{cde}	45.71^{cde}	42.48^{ef}	39.96^{f}
15	53.28^{b}	47.20^{cde}	46.21^{cde}	44.15^{def}
18	65.21^{a}	48.33^{bcd}	48.73^{bcd}	44.40^{def}
21	51.01^{bc}	46.24^{cde}	46.93^{cde}	44.64^{def}
$LSD_{(0.05)}$	5.53			
CV (%)	6.87			
P-value	<0.0001			

Means followed by the same letters are not significantly different (P > 0.05) from each other; LSD= Least significant difference, CV=Coefficient of variation

Plants grown at depth of 15cm combined with intra row spacing of 15cm produced the second highest total tuber yield (52.38t ha^{-1}) which exhibited statistically non-significant difference with total tuber yields produced from treatment combination of 12cmx15cm and 18cmx20cm.

According to this study maximum yield was obtained at closer in row plant spacing (15cm) combined with all level of planting depth than wider intra row combinations with different levels planting depth. In other way planting depth of 18cm combined with varies levels of intra row spacing produced higher yield than other tested level of depth combination with varies levels of intra row spacing (Table 10). This is might be the compensation effect of closer (15cm) intra row spaced plants per hectare than the wider intra row spacing which is the high numbers of stem per unit area resulted in higher yield of tubers. Similarly, the optimum depth is allowed the potato to get more food reserves and water encouraging development of more number nodes, stolen and increasing fresh weight of tubers (Chehaibi *et al*., 2013). The soil moisture favorable for plants led to an increase of the number of tubers (Krystyna, 2013). In the same way presence of high number of stems per unit area which attributed to the production of many stems leads to the production of high number tubers and consequently high total tuber yield per hectare (Sanli *et al.*, 2015). The increased yield at higher densities is also due to the ground being covered with green leaves earlier (earlier in the season, light is intercepted and used for assimilation), fewer lateral branches are being formed and tuber growth starting earlier (Harnet *et al*., 2014).

The present result also agrees with the findings of Harnet *et al*. (2014) who reported that the yield of seed tuber per hectare was increased with decreasing plant spacing in which the increased in yield was attributed to more tubers produced at the higher plant population per hectare. Similarly Zabihi *et al.* (2011) reported that plant density in potato affects some of the important plant traits such as total yield, tuber size distribution and tuber quality. From their finding they suggested that, the increase in plant density led to decrease in mean tuber weight but number of tubers and yield per unit area were increased. Bikila *et al.* (2014b) also indicated that the amount of yield, tuber number, increased as the spacing between plants and rows decreased and the increased in yield was mainly attributed to more number of tubers produced at the higher plant population per hectare. In contrast, Berga *et al*. (1994) reported that wider row width by wider in-row distance (80 x 40 cm) gave the highest yield (34 t ha^{-1}) and the 60 x 20 treatment gave the lowest yield (22.2 t ha^{-1}).The difference in report between current study and previous work of Berga *et al. (*1994) might be due to the experiment was conducted at different season, used different varieties and the experiment setup also widely different.

4.2.8. Marketable seed tuber yield

Planting depth and intra row plant spacing significantly (P <0.05) influenced marketable tuber yield and the two factors also interacted to influence the parameter (Table 11 and Appendix Table 3). The highest marketable seed tuber yield (58.60 t ha^{-1}) was obtained in response to planting the tubers at depth of 18cm combined with intra row plant spacing of 15cm followed by yield (47.96 t ha^{-1}) recorded from treatment of 15cm x15cm depth and intra row spacing. However the lowest marketable tuber yield (35.22 t ha^{-1}) was recorded at depth and intra row combination of 12cm x 30cm which was statically similar with the yield recorded at treatments of 12cmx25cm, 15cmx30cm, 18cmx30cm and 12cm x15cm depth and intra row spacing (Table 11).

Table 11. Interaction effect of planting depth and intra row plant spacing on marketable seed tuber yield (t ha^{-1}) at HARC under irrigation in the 2015 off season (February-June).

Planting depth(cm)	Intra row spacing (cm)			
	15	20	25	30
12	40.14^{de}	41.14^{cd}	38.40^{de}	35.22^{e}
15	47.96^{b}	43.30^{bcd}	41.68^{cd}	39.55^{de}
18	58.60^{a}	43.61^{bcd}	44.08^{bcd}	39.94^{de}
21	46.22^{bc}	41.39^{cd}	43.32^{bcd}	43.16^{bcd}
$LSD_{(0.05)}$	5.79			
CV (%)	8.02			
P-value	0.0106			

Means followed by the same letters are not significantly different (P > 0.05) from each other; LSD= Least significant difference, CV=Coefficient of variation

Marketable yield recorded at depth of 18cm combined with intra row spacing of 15cm is higher than treatment combinations of 12cmx25cm and 12 x 30 cm by about 34.47 and 39.9 %, respectively. Similarly, marketable tuber yield harvested at treatment combination of 15cm depth with 15 cm intra row plant spacing exceeded that of 12 x 25 cm and 12x30cm by about 19.93 and 26.56%, respectively (Table 11).

Similar to total tuber yield an optimum marketable yield was obtained at closer (15cm) intra row plant spacing combined with most levelsof planting depth than combinations of wider in row spacing with different levels of planting depth. This could be due to the combination of closer intra row spacing with optimum depth which had better soil conditions for proper root growth and nutrient absorption that facilitate the above ground part for better growth and development and the presence of high stem numbers per unit area produced high number of tubers which ultimately resulted for better marketable tuber yield. At closer intra row spacing due the presence of high stem numbers per unit area, there is a possibility of high number of tubers due early canopy coverage which absorbed the sufficiently available resources and intercepted more light and increased their photosynthetic efficiency for higher photo assimilate production and ultimately resulted in increased more marketable tuber yield mainly as seed. As the number of tubers per hectare increases there is a chance of obtaining greater amount of tuber yields that can be marketed than in the low number of tubers per hectare. The marketable yield reduction at the shallow depth combination with wider intra row spacing was presumably due to increase in insect damaged tuber and production of low tuber yield per unit area. The largest impact to marketable yield and gross income came from undersized and insect damaged tubers. Tuber damaged by insect was reduced as seed pieces were planted deeper. Pavek and Thornton, (2009) result show that marketable yield and gross income typically declined when seed pieces were planted shallow (10 cm).

This result is consistent with the result reported by Harnet *et al. (*2014) that the highest marketable yield recorded at closer spacing is attributed to more tubers produced at higher plant population per hectare. Similarly, Khalafalla (2001) reported regarding plant density effect on marketability of the crop. Spacing of 15-25 cm was reported to give better proportion of marketable yield than wider spacing of 35 cm. Bikila *et al*. (2014b) also stated that in the narrower treatment combination, 65x20 cm highest marketable tuber yield (37.02 t ha^{-1}) were observed than in the wider spacing combinations. As the number of tubers ha^{-1} increases there is a chance of obtaining greater amount of tuber yields that can be marketed than in the reduced number of tubers ha^{-1}.

4.2.9. Unmarketable tuber yield

The interaction of the two main factors planting depth and intra row spacing had significantly ($P<0.05$) affected unmarketable tuber yield (Table 12 and Appendix Table 3). The lowest unmarketable tuber yield (1.48 t ha^{-1}) was recorded at the combination of deeper depth (21cm) and wider intra row plant spacing (30cm). While the highest unmarketable tuber yield (7.28 t ha^{-1}) was recorded from crops grown at planting depth of 12cm combined with closer intra row plant spacing (15cm) which was statistically similar with result obtained at treatment combination of 18cmx15cm (Table 12). Tuber yield harvested from plants grown at closer intra row spacing (15cm) combined with most levels of planting depth had high unmarketable yield which was higher than those harvested from wider intra row (30cm) combined with planting depth of 12cm, 15cm, and 21cm by about 38.43, 26.60 and 60.24%, respectively.

Table 12. Interaction effect of planting depth and intra row plant spacing on unmarketable tubers yield (t ha^{-1}) at HARC under irrigation in the 2015 off season (February-June).

Planting depth(cm)	Intra row spacing (cm)			
	15	20	25	30
12	7.28^{a}	4.58^{bcd}	4.08^{cd}	4.75^{bcd}
15	5.31^{b}	3.90^{cd}	4.53^{bcd}	4.60^{bcd}
18	6.61^{a}	4.72^{bcd}	4.65^{bcd}	4.46^{bcd}
21	4.79^{bcd}	4.85^{bc}	3.61^{d}	1.49^{e}
$LSD_{(0.05)}$	1.23			
CV (%)	16.40			
P-value	0.0022			

Means followed by the same letters are not significantly different ($P > 0.05$) from each other; LSD= Least significant difference, CV=Coefficient of variation

This study show that plants grown at closer spacing combined with most levels of planting depth produced high unmarketable tuber yield than the one grown at wider intra row space combination with varies level of planting depth. As intra row plant spacing increases from 15 cm to 30 cm, the unmarketable tuber yield reduced. The increased in plant density at relatively shallow depth the yield of unmarketable tuber yield increased. This might be due to closer intra row plant spacing had high competition of plants for growth factors due to high number of plant per unit area which lead to produce high number of under size tubers and at shallow depth most of the produced tubers are exposed to external environment due lack of enough soil volume then easily exposed to external environment and attacked by different insects especially potato tuber moth. Thus, the cumulative of under sized and damaged tubers, were resulted higher unmarketable tuber yield than combination of wider intra row spacing with deeper depth.

This result in line with the results of Frezgi (2007)who reported that closest spacing which resulted in significantly higher yield of small tubers as the consequence of higher competition between plants. Tesfaye *et al*. (2012) also indicated that at closer plant spacing produced high yield of unmarketable tubers than wider plant spacing.

4.3. Physical Quality Parameters

The results obtained in terms of potato quality parameters such as tuber size categories (under, small, medium and large tubers m^{-2}), tuber specific gravity and dry matter content (%) are presented and discussed.

4.3.1. Number and yield of under sized tubers (<25mm)

Interaction of the two main factors planting depth and intra row spacing had significantly ($P<0.05$) affected number and yield of under sized tubers, respectively (Table 13 and Appendix Table 4 and 5). The lowest number and yield of under sized tubers (4.17 and 67.56g m^{-2}) were recorded from plants grown at treatment combination of depth and intra row plant spacing 21cm x 30cm which was statically at par with number and yield of under sized tubers gained from combination of depth and in row plant spacing of 12cm x 30cm and 15cm x30cm (Table.13). However, highest number and yield of under sized tubers (15.93 and 407.27 g m^{-2}) were obtained from potato grown at depth of 18cm combined with intra row plant spacing of 15cm followed by tuber number and yield obtained from plants grown at treatment of 15cm x15cm depth and intra row plant spacing which show statistically difference with treatment combination of 12cm x 15cm for number of tubers while no significance variation for the yield of under sized tubers m^{-2} (Table 13).

Table 13. Interaction effect of planting depth and intra row plant spacing on mean number and yield of under sized tubers m^{-2} at HARC under irrigation in the 2015 off season (February-June).

Planting depth(cm)	Intra row spacing(cm)	Tuber number (m^{-2})	Tuber yield (g m^{-2})
12	15	12.59^{c}	262.65^{b}
	20	9.17^{f}	176.79^{cde}
	25	6.02^{ghi}	137.39^{fgh}
	30	4.63^{j}	87.51^{jk}
15	15	14.54^{b}	277.62^{b}
	20	10.00^{ef}	200.65^{c}
	25	6.48^{gh}	149.87^{efg}
	30	5.00^{ji}	105.84^{ij}
18	15	15.93^{a}	407.21^{a}
	20	$11.11d^{e}$	207.00^{c}
	25	7.13^{g}	159.72^{def}
	30	5.83^{hi}	$116.99^{hi}j$
21	15	11.7^{6cd}	249.90^{b}
	20	9.72^{f}	183.26^{cd}
	25	6.11^{ghi}	123.72^{ghi}
	30	4.17^{j}	67.56^{k}
LSD $_{(0.05)}$		1.11	31.46
CV (%)		7.29	10.43
P-value		0.0061	<0.0001

Means followed by the same letter within a column are not significantly different (P > 0.05) from each other; LSD= Least significant difference, CV= Coefficient of variation

Based on this study plants grown at closer intra row plant spacing combined with different levels of planting depth produced high number and yield of under sized tubers than combination of wider intra row plant spacing with different levels of planting depth. When plant density increased the number and yield of under sized tubers also increased which are the main contributors of unmarketable number of tubers and yield in potato seed production. This might be due to the combined effect of planting depth and intra row plant spacing that at proper depth the length of underground stem increased which produced more number of stolen resulted in more number of tubers and also due to the closer plant spacing there could be high number of plants m^{-2} which produced high number of potato tubers, then the tubers were exposed to limited photosynthetic product to bulk each of them uniformly. Thus, the produced tubers become smaller in size due to unequal distribution of photo assimilates and ultimately the numbers of under sized tubers were increased. It might be also closer intra row plant spacing there could be strong competition between plants for nutrient and growth factors which lead to produce high number and yield of under sized tubers. Undersized and small sized tubers are less desired because of the low market prices (Hossain *et al.,* 2011).

This result agrees with the finding of Sanli *et al.*(2015) reported that the proportion of larger tuber was the highest at the wider spacing and the non-marketable (under sized tuber) yield increased with increasing stem density due to greater competition for water, nutrients and sunlight during tuber bulking resulting in fewer assimilates available for each individual tuber. Berga *et al.* (1994) also explained that total number and seed sizes numbers (smaller tubers) increased with closer spacing. Similarly, Tesfaye *et al.* (2013) reported that the highest numbers of small tubers were obtained at closer plant spacing whereas the lowest numbers of small potato tubers were found at wider plant spacing. It was also reported as the closet spacing increased the number of undesired potato tubers result to economic loss for the farmers while medium sized tubers are the most desired ones for their seed value and higher market prices (Bikila *et al.,* 2014b). Bikila *et al.* (2014b)also indicated that increasing the spacing between plants and rows from 60x30cm to 85x40cm resulted to a 53% d creased in number of under sized (<20 mm) tubers from 81.66 to 38.66.

4.3.2. Number and yield of small sized tubers (25-35mm)

Number and yield of small sized tubers were significantly (P<0.01) affected by interaction between planting depth and intra row plant spacing (Table 14 and Appendix Table 4 and 5). The highest number and yield of small sized tubers (17.69 and 692.13g m^{-2}) were obtained from plants grown at depth and intra row spacing of 18cm x15cm followed by number and yield recorded from treatment combination of 15cmx15cm which are statically parity between them. The number and yield harvested from potato grown at depth and intra row spacing of 15cm x15cm was statically different from result obtained at depth of 12 and 21cm combined with intra spacing of 15cm (Table 14).

Table 14. Interaction effect of planting depth and intra row plant spacing on mean number and yield of s small sized tubers m^{-2} at HARC under irrigation in the 2015 off season (February-June).

Planting depth(cm)	Intra row spacing (cm)	Tuber number(m^{-2})	Tuber yield (g m^{-2})
12	15	13.89[b]	428.22[b]
	20	11.39[def]	395.76[b]
	25	9.54[gh]	378.75[b]
	30	8.89[h]	292.26[c]
15	15	16.39[a]	614.27[a]
	20	11.94[cde]	404.81[b]
	25	10.83[efg]	386.26[b]
	30	10.00[fgh]	377.40[b]
18	15	17.69[a]	692.13[a]
	20	12.50[bcd]	412.08[b]
	25	11.02[ef]	391.87[b]
	30	10.28[fgh]	379.06[b]
21	15	13.06[bc]	415.46[b]
	20	11.85[cde]	398.38[b]
	25	10.56[efg]	383.26[b]
	30	9.44[gh]	370.45[bc]
LSD $_{(0.05)}$		1.41	83.24
CV (%)		7.20	11.92
P-value		0.0072	0.0003

Means followed by the same letter within a column are not significantly different ($P > 0.05$) from each other; LSD= Least significant difference, CV= Coefficient of variation

However, the lowest number and yield of small sized tubers (8.89 and 292.26g m^{-2}) were recorded from potato grown at depth and intra row spacing of 12cmx30cm which was not statistically different from those harvested from depth of 21cm combined with the same intra row plant spacing (Table 14).The number and yield of small sized tubers obtained from treatment effect of 18cm depth with15cm intra row spacing is higher than the one gained from plants grown at depth and intra row plant spacing of 12cm x 30cm by about 57.77 and 49.75% of tuber numbers and yield, respectively.The combination of different levels of planting depth with closer intra row spacing resulted in more number and yield of small sized tubers than varies level of planting depth combined with wider intra row spacing. Closer plant spacing produced high number and yield of small sized tuber than wider plant spacing. This might be due to the combined effect of planting depth and intra row plant spacing that at proper depth the length of underground stem increased which produced more number of stolen and resulted in more number of tubers. Due to closer plant spacing there could be high number of plants per meter square which resulted in high number of stems which in turn produced more number of tubers, and then the produced tubers were exposed to limited sources of photosynthetic product to bulk each of them uniformly. Thus, the produced tubers become smaller in size due to unequal distribution of photo assimilates and ultimately the numbers of small sized tubers were increased. It might be also closer intra row plant spacing there could be strong competition between plants for nutrient and growth factors which lead to produce high number and yield of small sized tubers.

This result agrees with the finding of Berga *et al.* (1994) reported that total number and seed sized numbers (smaller tubers) increased with closer spacing. Similarly, Tesfaye *et al*. (2013) reported that the highest number of small tubers was obtained at closer plant spacing whereas the lowest numbers of small potato tubers were found at wider plant spacing. Bikila *et al*. (2014b) also reported that number of small sized tuber (20-30 mm) was also decreased from 86 to 26 as the spacing increased from 60x30 cm to 75x30cm. It was also reported that the increase in plant density decreases mean tuber size, due to a reduction in plant nutrient elements, and increase in interspecies competition, however, large number of tubers was produced because of high numbers of stems per unit area (Khajehpour, 2006).

4.3.3. Number and yield of medium sized tuber (35-55mm)

The interaction of planting depth and intra row plant spacing had significant ($P<0.05$) influence on number and yield of medium sized tubers, respectively (Table 15 and Appendix Table 4 and 5).The maximum number and yield of medium sized tubers (35.46 and 3841.10g m^{-2}) were obtained from plants grown at depth and intra row spacing of 18cm by 15 cm followed by treatment combination of 15cm by 15cm (Table 15). However, the lower number and yield of medium sized tubers (12.22 and 1210.60g m^{-2}) were gained from potato grown at treatment combination of depth and intra row spacing 12cmx30cm, which was statistically at par with treatment combination of 21x30cm, 15cmx30cm and 18x30cm (Table 15).

Table 15. Interaction effect of planting depth and intra row plant spacing on mean number and yield of medium sized tubers m^{-2} at HARC under irrigation in the 2015 off season (February-June).

Planting depth (cm)	Intra row spacing (cm)	Tuber number (m^{-2})	Tuber yield (g m^{-2})
12	15	22.41^{c}	2565.20^{bc}
	20	18.61^{de}	2322.80^{cde}
	25	14.26^{hi}	1692.90^{fg}
	30	12.22^{j}	1210.60^{h}
15	15	31.57^{b}	2878.20^{b}
	20	19.44^{d}	2403.80^{dc}
	25	16.48^{fg}	1992.00^{ef}
	30	13.52^{ij}	1488.70^{gh}
18	15	35.46^{a}	3841.10^{a}
	20	22.13^{c}	2436.90^{cd}
	25	17.50^{efg}	2144.30^{de}
	30	14.07^{hij}	1493.30^{gh}
21	15	23.24^{c}	2825.90^{b}
	20	18.06^{def}	2214.80^{cde}
	25	15.65^{gh}	1959.30^{fe}
	30	13.06^{ij}	1483.10^{gh}
LSD $_{(0.05)}$		1.88	363.48
CV (%)		5.76	9.57
P-value		<0.0001	0.0015

Means followed by the same letter within a column are not significantly different (P > 0.05) from each other; LSD= Least significant difference, CV= Coefficient of variation

The treatment effect of depth and intra row spacing of 15cm x15cm produced numbers of medium sized tubers statistically different from result obtained from crops grown at depth of 12cm and 21cm combined with the same level of in row spacing (15cm) while the harvested yield was statistically at par (Table 15). The trend show that, number and yield of medium sized tubers m^{-2} were increased as plants grown at depth of 15 and 18cm combined with closer intra row plant spacing (15cm) than plants grown at this depth with combination of wider plant spacing of 30cm (Table 15). The number and yield of medium sized tubers recorded at treatment of 18cm x 20 cm depth and intra row plant spacing did not show statistically difference from treatment combination of 15cm x 20 cm, 12 x 20 cm and 21cm x 20 cm depth and in row plant spacing (Table 15).

The decreased in intra row plant spacing at planting depth of 18cm the number and yield of medium sized tubers were increased. This might be due to proper planting depth combined with closer intra row plant spacing had high numbers of hills with longer underground stem per unit area which lead to produce higher number of stems and stolen which resulted in more tubers than wider plant spacing. The advantage of getting more medium sized tubers is higher from more tuber production than less tuber production.

This study agrees with Wiresma (1987) results who reported that the number of tubers produced depends on the competition of among stems for growth factors, such nutrients, water and light. At lower stem densities competition is less, which results a greater number of tuber per stem, but also in a smaller number of tubers per unit area. On the other hand, when stem densities increase, the number of tubers per stem decrease, but the number of tuber per unit area generally increases. At high stem density increase yield up to a certain level, reduce average tuber size reduces the number of tubers produced from one seed tuber

4.3.4. Number and yield of large sized tubers (>55mm)

The analysis of variance result show that potato variety was significantly ($P<0.05$) influenced in producing number of large sized tubers due to planting depth and significantly ($P<0.05$) affected in producing number and yield of large sized tubers due to intra row plant spacing. However, the main effect of planting depth on yield of large sized tubers and the interaction effect of the two main factors on number and yield of large sized tubers have found no significant (Table 16 and Appendix Table 4 and 5). The maximum numbers of large sized tubers (8.06 m^{-2}) were obtained from potato grown at depth of 21cm followed by those harvested from plants grown at depth of 18cm although no significant difference between them (Table 16). The low number of large sized tubers (7.20 m^{-2}) was obtained at relatively shallow planting depth (12cm) which was not statistically different from numbers of large sized tubers harvested from potato grown at depth of 15cm and 18cm (Table 16). Plants grown at deeper depth (21cm) produced number of large sized tubers which exceeds those numbers recorded from potato grown at relatively shallow depth (12cm) by about 10.65%. In this study number of large sized tubers per meter square was increased as plants grown at deeper depth than plants grown shallow depth. This could be due to the fact that planting the potato at deeper depth had better soil conditions for moisture conservation, root penetration and nutrient absorption. Therefore, plants absorbed the sufficiently available resources and increased their photosynthetic efficiency that ultimately increased the number of large sized tubers.

Table 16. Main effect of planting depth and intra row spacing on number and yield of large sized tubers at HARC under irrigation in the 2015 off season (February-June).

Treatment	Tuber number (m^{-2})	Tuber yield ($g\ m^{-2}$)
Planting depth (cm)		
12	7.20^{b}	1901.57^{a}
15	7.48^{ab}	1950.94^{a}
18	7.78^{ab}	1996.39^{a}
21	8.06^{a}	2052.01^{a}
$LSD_{(0.05)}$	0.60	222.43
P-value	0.0382	0.5626
Intra row spacing (cm)		
15	5.44^{d}	1558.44^{c}
20	6.53^{c}	1747.80^{c}
25	8.15^{b}	2133.92^{b}
30	10.39^{a}	2460.75^{a}
$LSD_{(0.05)}$	0.60	222.43
P-value	<0.0001	<0.0001
CV (%)	9.44	13.51

Means followed by the same letter within a column are not significantly different ($P > 0.05$) from each other; LSD= Least significant difference, CV= Coefficient of variation

In case of intra row spacing, the maximum numbers and yield of large sized tubers (10.39 and 2460.75g m^{-2})were obtained from plants grown at intra row spacing of 30 cm whereas the low number and yield of large sized tubers(8.15 and 2133.92g m^{-2}) were recorded from intra row spacing of 15cm. Plants grown at intra row spacing of 25 cm also produced number and yield of large sized tubers statistically different from plants grown at in row spacing of 20 and 15cm (Table 16). The result revealed that potato grown at intra row spacing of 30 cm produced number and yields of large sized tubers higher than result gained from intra row spacing of 25cm,20cm and 15cm by about 21.56 and 13.28, 37.15 and 28.97, 47.64 and 36.67 % of number of tubers and yield, respectively.

Present result show that the number and yield of large sized tubers m^{-2} were increased as plants grown at wider intra row spacing (30cm) compared to grown at closer intra row plant spacing (15cm). This could be due to the availability of adequate space for root and tuber expansion and presence of minimum competition; plants absorbed the sufficiently available resources and increased their photosynthetic efficiency which finally resulted in more number of large sized tubers. Therefore, the slight competition between plants for nutrients and growth factors were increased photosynthesis efficiency of plants and more photos assimilate distributed to tubers uniformly.

The present finding is in agreement with the work of Tesfaye *et al*. (2013) who reported that highest number of large tuber sizes was recorded at wider plant spacing due to minimum competition of plants, absorbed sufficient available resources and increased their photosynthesis efficiency that ultimately increased number of large tubers. Similarly Gebremedhin *et al*. (2008b), Gulluoglu and Arioglu (2009), Tafi *et al.* (2010) and Harnet *et al.* (2013) also reported that the production of large tubers increased in the wider plant spacing due to less competition for nutrients and moisture compared to the closer plant spacing.

4.3.5. Specific gravity of tubers (g/cm^3)

The main factors of planting depth and intra row plant spacing as well as the interaction had no significant effect on specific gravity at 5% probability level of significance (Table 17 and Appendix Table 4). However, planting depth and intra row plant spacing recorded had high specific gravity of seed tubers which is in between 1.13 to 1.17 (Table 17). As a result, the main factors of depth and intra row plant spacing are grouped under high specific gravity grades, which are acceptable standards for tuber quality in terms of dry matters, starch and total soluble solid contents which determined the processing quality for chips and crisp. Seed potatoes with a high specific gravity have been reported to produce higher yields than potatoes with low specific gravity (USAID, 2011).The main factor of planting depth and intra row plant spacing did not affect tuber specific gravity. This might be due to the fact that this trait is controlled by genetic factors rather than by planting depth and intra row plant spacing.

In this study, only one variety was used as experimental material in which specific gravity parameter was not affected by planting depth and intra row plant spacing.

This result is in agreement with the finding of Bikila *et al.* (2014b) who reported that tuber specific gravity was not affected by inter and intra row spacing. Similarly, Rykbost and Maxwell (1993) reported that plant population not to have an effect on the specific gravity of all the varieties they studied. Moreover, reports from many attempts have been indicated that variety has the most important factor in determining potato quality (Hegney, 2005; Musa *et al.,* 2007; Abubaker *et al.,* 2011).

Table 17. Main effect of planting depth and intra row spacing on specific gravity and tuber dry matter content at HARC under irrigation in the 2015 off season (February-June).

Treatment	Specific gravity (g/cm^3)	Tuber dry matter content (%)
Planting depth (cm)		
12	1.16[a]	24.94[a]
15	1.17[a]	24.36[a]
18	1.14[a]	24.94[a]
21	1.13[a]	24.20[a]
LSD $_{(0.05)}$	0.04	1.08
P-value	0. 3209	0.3688
Intra row spacing (cm)		
15	1.17[a]	24.39[a]
20	1.16[a]	24.22[a]
25	1.16[a]	25.04[a]
30	1.13[a]	24.79[a]
LSD$_{(0.05)}$	0.04	1.08
CV (%)	4.65	5.24
P-value	0.409	0.3972

Means followed by the same letter within a column are not significantly different (P > 0.05) from each other; LSD= Least significant difference, CV= Coefficient of variation

4.3.6. Tuber dry matter content (%)

The effect of planting depth and intra row plant spacing had no significant difference on dry matter content of tubers. Similarly the two factors interaction had no effect on dry matter content (Table 17 and Appendix Table 4). This study show that planting depth and intra row spacing had recorded tuber dry matter contents in the range of 24.20-24.94% and 24.22-24.79 % respectively. As a result, the main factors of planting depth and intra row plant spacing gave a high tuber dry matter content which was greater than 20% which is preferred for processing and for strong seedling establishment and increase tuberization of subsequent plants. Similarly, Kabira and Berga (2006) reported that tuber dry matter contents of more than 20% are acceptable for processing of chips and crisp. Tesfaye *et al.* (2013) also reported that Potato tuber with dry matter contents greater than 20% is the most preferred for processing of tuber into different potato products.

The main factor of planting depth and intra row plant spacing did not affect tuber dry matter content. This could be due to this trait is controlled by genetic factors rather than by planting depth and intra row plant spacing. In this study, only one variety namely, Belete was used as experimental material where dry matter content parameter was not affected by the planting depth and intra row plant spacing. The result in disagreement with the findings of Tesfaye *et al.* (2013) who reported that high plant population associated with low dry matter content because of high competition for light and other important resources and this then led to a few resources being channeled to each sink.

4.4. Correlation Analysis among Growth and Yield Parameters

Correlation analysis among growth and yield parameters showed that plant height ($r = 0.5$), total tuber number ($r=0.91$), marketable tuber number ($r=0.94$) unmarketable tuber number ($r=0.6$) marketable tuber yield ($r = 0.98$), and unmarketable tuber yield ($r=0.49$) correlated significantly ($P<0.05$) and positively with total tuber yield. These result showed that any positive increase in such characters had boasted total tuber yield (Table 18). These findings were in agreement with the results of other researches (Khayatnezhad *et al.*, 2011). On the other hand, negative and significant ($P<0.05$) correlations were showed between yield and Average tuber weight ($r = -0.66$)

Plant characters also showed significant association with one another. Similarly, marketable tuber yield associated positively and significantly ($P<0.05$) with total tubers number ($r=0.85$), marketable tubers number ($r=0.92$) and total tuber yield ($r=0.98$) while negatively to average tuber weight ($r = -0.55$). Plant height ($r = 0.71$), total tubers number ($r = 0.63$), unmarketable tubers number and total tuber yield were positively and significantly (P<0.05) correlated with unmarketable tuber yield while unmarketable tuber yield associated negatively with average tuber yield (r = -0.60, P<0.05) and average tuber weight (r = -0.70, P<0.01). Average tuber weight had highly significant (P<0.01) negative correlation with plant height (r = -0.83), total tuber number (r = -0.90), marketable tubers number (r = -0.76) and unmarketable tubers number (r = -0.94) while a highly significant (P<0.01) positive relation with average tuber yield (r =0 .85). In the same manner the average tuber yield had highly significant (P<0.01) negative association with plant height (r=-0.90), total tubers number (r=-0.66) and unmarketable tubers number (r=-90) and significantly (P<0.01) positive correlation with average tubers number (r=0.83) was observed.

Days to 50% emergency had significant (P<0.001) positive relation with days to 50% flowering (r = 0.91) and days to 50% maturity (r = 0.88) and days to 50% flowering had significant and positive relation with days to maturity (r = 0.99). Both days to flowering (r=-0.57) and days to maturity (r=-0.60) have significant (P< 0.05) negative relation with plant height. Among growth parameters plant height significantly and positively associated with most parameters of yield which includes, total number of tubers (r = 0.73), marketable number of tubers (r = 0.57), unmarketable number of tubers (r = 0.86), total tuber yield(r = 0.5) and unmarketable tuber yield (r = 0.70). In other way this trait associated negatively with average tuber number (r = -0.60), Average tuber yield (r =- 0.90) and average tuber weight (r = -0.83). This implied that factors that favors the increase in plant height result in increments of the parameters mentioned above which are positively related while decrease those negatively related to it.

In this study, it is proved that tuber number associated positively with total tuber yield which indicated that the former is an excellent indicator of the latter which agrees with the report of Tekalign and Hammes (2005). The relationship between total and marketable tuber yield with total and marketable number of tubers m^{-2} were positive and highly significant. This means that tuber numbers have more relation with yield and marketable tuber yield in which any condition that increase tuber number result in an increment in total and marketable tuber yield. From this point of view the yield gain recorded from the current study was due to production of more number of tubers.

Table 18. Pearson Correlation coefficient among growth and yield parameters of potato

	DE	DF	DM	PH	MSN	TTN	MTN	UTN	ATN	ATY	ATW	TTY	UTY	MTY
DE	1	0.91***	0.88**	-0.31^{ns}	-0.08^{ns}	0.10^{ns}	0.21^{ns}	-0.16^{ns}	0.15^{ns}	0.13^{ns}	0.08^{ns}	0.29^{ns}	-0.26^{ns}	0.38^{ns}
DF		1	0.99**	-0.57*	-0.06^{ns}	-0.16^{ns}	0.01^{ns}	-0.47^{ns}	0.36^{ns}	0.45^{ns}	0.39^{ns}	0.08^{ns}	-0.50^{ns}	0.21^{ns}
DM			1	-0.60**	-0.12^{ns}	-0.19^{ns}	-0.02^{ns}	-0.49*	0.40^{ns}	0.48^{ns}	0.41^{ns}	0.06^{ns}	-0.49^{ns}	0.18^{ns}
PH				1	-0.09^{ns}	0.73**	0.57*	0.86**	-0.68**	-0.90**	-0.83***	0.50*	0.70**	0.38^{ns}
MSN					1	-0.12^{ns}	-0.06^{ns}	-0.23^{ns}	0.22^{ns}	0.23^{ns}	0.16^{ns}	-0.10^{ns}	-0.04^{ns}	-0.10^{ns}
TTN						1	0.96***	0.819***	-0.19^{ns}	-0.66**	-0.90***	0.91**	0.63**	0.85***
MTN							1	0.62**	0.02^{ns}	-0.46^{ns}	-0.76**	0.94**	0.48^{ns}	0.92***
UTN								1	-0.57*	-0.90**	-0.94***	0.60*	0.79**	0.47^{ns}
ATN									1	0.83**	0.42^{ns}	0.06^{ns}	-0.30^{ns}	0.07^{ns}
ATY										1	0.85***	-0.41^{ns}	-0.60*	-0.31^{ns}
ATW											1	-0.66**	-0.71**	-0.55*
TTY												1	0.49*	0.98**
UTY													1	0.29^{ns}
MTY														1

*.= Correlation is significant at the 0.05 level. **= Correlation is significant at the 0.01 level. ***= Correlation is significant at the 0.001 level DE= Days to emergence, DF=Days to flowering, DM=Days to maturity, PH= Plant height, MSN=Main stem number, TTN=Total tuber number, MTN= Marketable tuber number, UTN= Unmarketable tuber number, ATN= Average tuber number, ATY=Average tuber yield, ATW = Average Tuber Weight, TTY=Total tuber yield, UTY=Unmarketable tuber yield and MTY=Marketable tuber yield

5. SUMMARY AND CONCLUSION

5.1. Summary

Potato is the most economically important crop as a source of food and cash in Ethiopia. Appropriate planting depth and intra row spacing are important agronomic practices for increasing yield of seed and ware potato. However, varied planting depth and intra row spacing are used in Ethiopia by smallholder farmers as well as by researchers regardless of the type and purpose of cultivars being grown or the environmental conditions under which the crop is grown.

Therefore, a field experiment was conducted at HARC with the objectives of determining the effect of planting depth and intra row plant spacing on growth, seed tuber yield and quality of potato under Holetta condition. The treatments consisted of four levels of planting depth (12cm, 15cm, 18cm and 21cm) and intra row plant spacing (15cm, 20cm, 25cm and 30 cm) which resulted in 16 treatment combination. The design used was 4x4 factorial experiment arranged in a Randomized Complete Block Design, replicated three times. Potato growth, seed tuber yield and physical quality parameters were collected and data were analyzed using SAS Version 9.0 statistical software.

The results of the experiment revealed significant and highly significant response of most growth, seed tuber yield and quality parameters to the main and interaction effects of depth and intra row plant spacing. Growth parameters (e.g., days to emergency, flowering, physiological maturity and plant height,) average tuber yield hill^{-1}, average tuber weight, number and yield of large sized tubers m^{-2}, were significantly affected by the main effects of planting depth and intra row spacing. The interaction effect of planting depth and intra row spacing was highly significant on average tuber number hill^{-1}, average, marketable and unmarketable number of tubers m^{-2} and yield of total tuber, marketable seed tuber and unmarketable tuber ha^{-1} as well as number and yield of different tuber size categories (under, small, and medium sized).

The growth parameters studied in the present study were significantly affected by the treatment main effects except for the number of main stems. Potato grown at deeper depth

(21cm) took significantly longer days to 50% emergence, flowering and physiological maturity compared to shallow planting depth (12cm). However plants grown at shallow depth produced the tallest plants compared to those grown at deeper depth. Similarly, potato grown at wider (30cm) intra row spacing took the longest (64.5 and 89.75) days for flowering and maturity, respectively. Plants at intra row spacing of 15cm were the tallest in height which increased by 9.58cm compared to intra row spacing of 30cm.

Considering the yield parameters, the highest value of average number of tubers (9.15 $hill^{-1}$) was recorded at interaction of 18cm x30cm depth and intra row spacing. The interaction of 21cmx15cm depth and intra row spacing resulted in lowest number of tubers (6.05$hill^{-1}$). The combined effect of 18cm x15cm depth and intra row spacing produced the highest average and marketable number of tubers. The lowest average and marketable number of tubers was gained from 12cm x 30cm depth and intra row spacing combination. While interaction of 12cm x15cm and 21cm x 30cm depth and intra row spacing resulted in maximum (18.43 m^{-2}) and minimum (5 m^{-2}) number of unmarketable tubers, respectively. As whole the number of tubers gained from interaction of 18cm x15cm depth and intra row spacing was higher than those gained from 15cm x 15 cm, 12cm x 15cm and 21cm x15cm by about 9.05, 28 and 28 %, respectively. Similarly, marketable tubers obtained at combination of 18cm x15cm depth and intra row spacing was higher than interaction of 15cm x 15cm and 21 x 15 cm by 10.89 and 33.28%, respectively.

Average tuber yield $hill^{-1}$ and average tuber weight was affected by the main effect of planting depth and intra row spacing as oppose to the number of tubers which affected by the interaction the two factors. Plants grown at depth of 18cm and 12cm produced highest and lowest average tuber yield $hill^{-1}$, respectively. Plants grown at the depth of 18cm significantly exceeded in producing mean tubers yield $hill^{-1}$ than those grown at the depth of 12cm, 15cm, and 21cm by about 13.54, 6.05 and 6.5%, respectively. Tubers harvested from wider intra row spacing (30cm) were superior in average tuber yield $hill^{-1}$ and also resulted in heaviest average tuber weight.

The highest total and marketable seed tuber yield (65.35 and 58.60 t ha^{-1}, respectively) was recorded from depth of 18cm combined with intra row spacing of 15cm while the lowest yield of total and marketable tubers (39.95 and 35.22 t ha^{-1}) was obtained at interaction of 12cmx30cm depth and intra row spacing. The highest unmarketable tuber yield (7.28 ton ha^{-1}) was recorded due to interaction effect of 12cm x15cm depth and intra row spacing where as the lowest one (1.48 t ha^{-1}) was resulted from combination of 21cm x 30cm depth and intra row spacing. The interaction effect of 18cm x15cm depth and intra row spacing resulted in tuber yield which exceeded total tuber yield harvested from 15cm x 15 cm, 12cm x 30cm and 12cm x25cm by about 18.29, 38.72 and 34.86 %, respectively. Similarly, marketable yield recorded at depth of 18cm combined with intra row spacing of 15cm was higher than treatment of 12cm x25cm and 12cm x 30 cm by about 34.47 and 39.9 %, respectively. In general, the widest spacing combined with all levels of planting depth (low planting density) reduced tuber yield compared to the higher plant population with different levels planting depth which resulted in higher number and yields of both total and marketable tubers per hectare.

The number and yield of different size of tubers showed highly significant variation in response to the interaction effects of planting depth and intra row spacing. The result indicated that higher number and yield of undersize (25mm), small size (25-35mm) and medium size (35-55mm) tubers were obtained from combination of closer (15cm) intra row plant spacing with varies level planting depth and large tuber size(>55mm) number and yield was increased at wider plant spacing and deeper depth. From this study, the highest number and yield of under, small and medium sized tubers (15.93 and 407.27g, 17.69 and 692.13g, 35.46 and 3841.1g per m^2, respectively) were obtained from treatment of 18 cm x 15 cm depth and intra row spacing. Treatment combination of 15cm x 15 cm depth and intra row spacing also resulted in high number and yield of (31.57 and 2878g per m^2 ,respectively) medium-sized tubers. However, various planting depth combination with wider intra row resulted in lowest number and yield of medium sized tubers compared to their combination with closer intra row spacing. Generally, number and yield of seed sized (small and medium-sized) potato tubers decreased with increasing intra row spacing.

Although the interaction and the main effects of planting depth and intra row spacing did not significantly influence the specific gravity and dry matter contents of tubers; the trend showed high specific gravity and dry matter percentage of tubers which is between 1.13 to 1.17 g/cm^3

and 24.20-24.94%, respectively for both planting depth and intra row spacing. As a result, the main factors of depth and intra row plant spacing are grouped under high specific gravity grades and tuber dry matter content, which are acceptable standards for tuber quality either for chips or crisp and a crucial importance in improving the vigor of seedlings and tuberization capacity of the resultant plants.

The simple correlation analysis showed that total seed tuber yield was positively and highly significantly correlated with, plant height, total tuber number, marketable tuber number and marketable tuber yield while negatively to average tuber weight and average tuber yield. This implied that any factors that increase on plant height and tubers number resulted in increment of seed tuber yield where as factors resulted in increment for average tuber weight and average tuber yield hill^{-1} decrease in seed tuber yield. According this study, this could be justified as the high yield gained is due to more number of tubers produced per unit area.

5.2. Conclusion

The study revealed that treatment combination of 18 x 15 cm, 15 x 15 cm and 18 x 20 cm depth and intra row spacing resulted in higher total and marketable tuber yields than the other treatment combination. For all levels of planting depth, the intra row spacing 15cm and 20cm led to the production of maximum seed sized (marketable seed) number of tubers and yield. Hence, the present study indicated that combination of planting depth of 15cm -18cm with intra row spacing of 15 -20cm can be used as preliminary information for further investigation to get optimum depth and intra row spacing for high marketable seed tuber yield with better quality.

Therefore, the recommendation of using planting depth of 10-15cm and intra row spacing of 30 cm between plants for all potato cultivars in the country so far should be revised and optimum depth and intra row spacing should be determined for specific regions considering the recent cultivars under production and the purpose for which it is being cultivated.

5.3. Future Line of Work

- The present study was done only for one season at one location; the experiment should be repeated for more years and locations to come up with comprehensive recommendations**.**
- Further study considering more number of varieties with different sources of seed is necessary to bring a recommendation which encompass all aspects of seed potato production and managemet.
- Since at different levels of intra row spacing the demand for seed per hectare is different, then there is need to study the economic benefit that will be gained by using various amount of seed in related to intra row spacing.

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8. APPENDICES

Appendix Table 1.Mean squares of potato growth parameters as affected by planting depth and intra row plant spacing

Source of variation	parameters					
	DF	Days to 50% Emergency	Days to 50% Flowering	Days to 50% maturity	Plant height(cm)	Main stem number
Blocks	2	0.25	0.27	1.33	3.15	1.65
Planting depth (cm)	3	123.78***	204.19***	174.24***	35.86**	0.25^{ns}
Intra row spacing(cm)	3	0.72^{ns}	22.85***	26.91***	198.81***	0.18^{ns}
Planting depth x intra row spacing(cm)	9	1.20^{ns}	3.78^{ns}	4.78^{ns}	2.44^{ns}	0.82^{ns}
Error	30	0.87	2.29	2.31	4.26	0.46
CV (%)		5.93	2.41	1.73	2.82	15.13
R^2		0.94	0.91	0.90	0.85	0.46
Mean		15.75	62.77	87.77	73.04	4.48
SD		2.96	4.09	3.91	4.28	0.74

*= significant, **= highly significant, *** = very highly significant, ns= non significant, DF =degree of freedom, CV= coefficient of variation, R^2= R-square, SD= standard deviation

Appendix Table 2. Mean squares of potato for average number of tubers per hill and average, marketable and unmarketable number of tubers per meter square as affected by planting depth and intra row plant spacing

Source of variation	Parameters				
	DF	Average number of tubers ($hill^{-1}$)	Average number of tubers (m^{-2})	Marketable number of tubers ($m^{-2)}$	Unmarketable number of tubers (m^{-2})
Blocks	2	0.02	1.62	0.76	1.42
Planting depth (cm)	3	4.76***	235.90***	205.69***	17.59***
Intra row spacing(cm)	3	5.89***	1424.29***	604.40***	200.91***
Planting depth x Intra row spacing(cm)	9	0.49**	52.89***	63.82***	2.92*
Error	30	0.09	3.18	2.63	0.98
CV (%)		3.99	3.76	4.58	8.25
R^2		0.93	0.98	0.97	0.96
Mean		7.65	47.45	35.46	11.98
SD		0.91	10.87	8.10	3.90

*= significant, **= highly significant, ***= very highly significant, ns= non significant, DF=degree of freedom, CV= coefficient of variation, R^2= R-square, SD= standard deviation

Appendix Table 3. Mean squares of potato for, average tuber, average tuber yield per hill weight and total, marketable and Unmarketable tuber yield, as affected by planting depth and intra row plant spacing

Source of variation	Parameters					
	DF	Average tuber weight (g)	Average tuber yield (g $hill^{-1}$)	Total tuber yield (ton ha^{-1})	Marketable tuber yield (ton ha^{-1})	Unmarketable tuber yield (ton ha^{-1})
Blocks	2	45.83	4262.53	16.26	15.57	0.03
Planting depth (cm)	3	128.07*	26295.91**	121.82***	124.94***	5.66**
Intra row spacing(cm)	3	1898.46***	322877.83***	261.37***	166.28***	10.80***
Planting depth x intra row spacing(cm)	9	45.27	4045.47	31.99*	36.01*	2.27**
Error	30	40.48	3197.88	10.69	11.87	0.58
CV (%)		6.19	7.16	6.87	8.02	16.4
R^2		0.84	0.92	0.82	0.78	0.80
Mean		102.72	790.09	47.62	42.98	4.64
SD		12.88	159.00	6.17	5.81	1.36

*= significant, **= highly significant, ***= very highly significant, ns= non significant, DF=Degree of freedom, CV= Coefficient of variation, R^2=R-square, SD= standard deviation

Appendix Table 4. Mean squares of potato for quality parameters (number of different tuber sizes, specific gravity and tuber dry matter content), as affected by planting depth and intra row plant spacing

Source of variation	Parameters						
	DF	Under sized number of tubers m^{-2}	Small sized number of tubers m^{-2}	Medium sized number of tubers m^{-2}	Large sized number of tubers m^{-2}	Specific gravity of tuber (g/cm^3)	Tuber dry matter content (%)
Blocks	2	1.02	0.58	2.06	0.84	0.0005	0.25
Planting depth (cm)	3	10.81***	9.91***	75.85***	1.65*	0.003^{ns}	1.81^{ns}
Intra row spacing(cm)	3	184.90***	73.13***	507.27***	55.67***	0.003^{ns}	1.70^{ns}
Planting depth x intra row spacing(cm)	9	1.37**	2.35**	21.23***	0.17^{ns}	0.003^{ns}	3.62^{ns}
Error	30	0.41	0.72	1.23	0.52	0.003	1.66
CV (%)		7.29	7.2	2.06	9.44	4.65	5.24
R^2		0.98	0.93	0.98	0.92	0.35	0.47
Mean		8.76	11.83	19.23	7.63	1.15	24.61
SD		3.61	2.50	6.49	2.01	0.05	1.41

*= significant, **= highly significant, ***= very highly significant, ns= non significant, DF=Degree of freedom, CV= Coefficient of variation, R^2= R-square, SD= standard deviation

Appendix Table 5. Mean squares of potato for yield of different tuber sizes, as affected by planting depth and intra row plant spacing

Source of variation	Parameters				
	DF	Under sized tuber yield (g m^{-2})	Small sized tuber yield (g m^{-2})	Medium sized tuber yield (g m^{-2})	Large sized tuber yield (g m^{-2})
Blocks	2	309.41	2455.85	109135.28	54146.64
Planting depth (cm)	3	10338.89***	23877.28**	587013.09***	49435.44^{ns}
Intra row spacing (cm)	3	92300.74***	78333.10***	5515588.87***	1945424.01***
Planting depth x Intra row spacing (cm)	9	2768.41***	12756.01***	181504.88**	1449.97^{ns}
Error	30	361.02	2508.27	43673.46	71172.34
CV (%)		10.43	11.92	5.76	13.51
R^2		0.97	0.85	0.98	0.74
Mean		182.11	420.03	2184.54	1975.23
SD		85.59	103.10	675.90	418.71

*= significant, **= highly significant, ***= very highly significant, ns= non significant, DF=Degree of freedom, CV= Coefficient of variation, R^2= R-square, SD= standard deviation