

**OPTIMIZING SOIL MATRIC POTENTIAL AND
CLIMATE BASED IRRIGATION SCHEDULING TO
POTATO UNDER DIFFERENT ESTABLISHMENT
METHODS**

Dissertation

**Submitted to the Punjab Agricultural University
in partial fulfillment of the requirements
for the degree of**

**DOCTORATE OF PHILOSOPHY
in
VEGETABLE SCIENCE
(Minor Subject: Soil Science)**

By

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(L-2010-A-30-D)**

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CERTIFICATE I

This is to certify that the dissertation entitled, “**Optimizing soil matric potential and climate based irrigation scheduling to potato under different establishment methods**” submitted for the degree of **Doctor of Philosophy**, in the subject of **Vegetable Science** (Minor subject: **Soil Science**) of the Punjab Agricultural University, Ludhiana, is a bonafide research work carried out by **Mr. Sanjeev Ahuja (L-2010-A-30-D)** under my supervision and that no part of this dissertation has been submitted for any other degree.

The assistance and help received during the course of investigation have been fully acknowledged.

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CERTIFICATE II

This is to certify that the dissertation entitled, “**Optimizing soil matric potential and climate based irrigation scheduling to potato under different establishment methods**” submitted by **Mr. Sanjeev Ahuja (L-2010-A-30-D)** to the Punjab Agricultural University, Ludhiana, in partial fulfillment of the requirements for the degree of **Doctor of Philosophy**, in the subject of **Vegetable Science** (Minor subject: **Soil Science**) has been approved by the Student’s Advisory Committee after an oral examination on the same.

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ABSTRACT

An Investigation under experiment-I was conducted with the objective to determine the most appropriate installation depth of tensiometer with suitable soil matric potential for higher tuber yield and water use efficiency of potato under furrow-ridge irrigation system at Vegetable Research Farm, Punjab Agricultural University, Ludhiana during 2011-12 and 2012-13. Three levels of soil matric suction (S); 20, 35 & 50 kPa at three installation depths (D) of tensiometer; 20, 30 & 40 cm and a control (traditional practice) were replicated thrice in RCBD. The pooled analysis of data showed that treatments $S_{20}D_{20}$ and $S_{35}D_{20}$ recorded 86 and 82% higher marketable tuber yield compared to the control. The WUE under $S_{35}D_{20}$ treatment was upto 177% higher than control when data was pooled over two years. Highest dry tuber yield was recorded in $S_{35}D_{20}$ treatment among all the treatments during both the years. The analysis of pooled data for marketable and graded tuber yield, average tuber weight, discarded percent of tubers, root dry weight, lower content of reducing sugars and higher percent of starch and protein content, plant height at harvest and above ground dry matter accumulation 30, 60 DAP and at harvest also favoured $S_{35}D_{20}$ and $S_{20}D_{20}$ treatments. However averaged over two years, WUE and WUE_i of $S_{35}D_{20}$ was more than double as compared to control treatment along with higher marketable tuber yield as 49 % irrigation water was saved. The results revealed that treatment $S_{35}D_{20}$ was the best treatment for irrigation scheduling in the region. Further, experiment-II was conducted in split plot design with four replications to compare the climatic based irrigation scheduling with $S_{35}D_{20}$ under ridge-furrow (M_1) and bed-furrow planting (M_2) system during 2012-13 and 2013-14. Two rows were planted on each bed under furrow-bed planting system. The treatments consisted of five irrigation levels: I_1 ; IWCPE (Irrigation water to cumulative pan evaporation) ratio 1.0, I_2 ; IWCPE ratio 1.25, I_3 ; IWCPE ratio 1.5, I_4 ; $S_{35}D_{20}$ (tensiometer installed at 20 cm soil depth maintaining SMP of -35 kPa) and I_5 ; control (farmers practice in the region). The ridge-furrow method of planting (M_1) showed its advantage over the bed-furrow method of planting (M_2) in terms of recording higher WUE, average tuber weight, marketable tuber yield, large and medium sized tuber yield, plant height at 60, 75 DAP and at harvest as well as above ground dry weight accumulation at the time of harvest. Almost three times higher water use efficiency was recorded by $S_{35}D_{20}$ as compared to control treatment (farmer's practice) under M_1 method of planting. This irrigation treatment was superior in terms of plant height, above ground DMA at 60 DAP and at harvest, graded and marketable tuber yield, starch and protein content and has lower discarded percent of tubers among all other treatments. The results of two experiments suggest that scheduling irrigation based on soil matric potential at -35 kPa SMP with tensiometer installing at soil depth of 20 cm under ridge-furrow irrigation system was better option under North-Western plains of India. Adopting this threshold corresponds to 3 to 4 irrigations of 45 to 45.5 mm each depending on the rainfall during potato growing period. Two separate irrigations of 50 mm each were applied, first as pre-planting irrigation and second irrigation to substantiate emergence. Thus, application of single irrigation two weeks after the complete emergence of crop and remaining 2-3 irrigations at 17 days interval may save irrigation water as compared to the traditional irrigation practice.

Keywords: Furrow-ridge irrigation system, marketable tuber yield, potato, soil water tension, tuber dry weight, water use efficiency

Signature of Major Advisor

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ਆਲੂ ਦਾ ਝਾੜ ਅਤੇ ਪਾਣੀ ਦੀ ਸੁਚੱਜੀ ਕਾਰਜ ਸਮਰੱਥਾ ਨੂੰ ਵਧਾਉਣ ਲਈ ਟੈਂਸੀਓਮੀਟਰ ਸਥਾਪਿਤ ਕਰਨ ਦੀ ਉੱਤਮ ਡੂੰਘਾਈ ਅਤੇ ਮਿੱਟੀ ਦੀ ਮੈਟ੍ਰਿਕ ਸਮਰੱਥਾ ਸੂਚੀ ਨੂੰ ਤਜਰਬਾ-I ਵਿੱਚ ਸਾਲ 2011-12 ਅਤੇ 2012-13 ਦੌਰਾਨ ਪੰਜਾਬ ਖੇਤੀਬਾੜੀ ਯੂਨੀਵਰਸਿਟੀ ਲੁਧਿਆਣਾ ਦੇ ਸਬਜ਼ੀ ਖੋਜ ਕੇਂਦਰ ਵਿਖੇ ਅਯੋਜਿਤ ਗਿਆ। ਅਧਿਐਨ ਦੌਰਾਨ ਕੀਤੇ ਗਏ ਤਜਰਬੇ ਵਿੱਚ ਟੈਂਸੀਓਮੀਟਰ ਦੀਆਂ ਤਿੰਨ ਸਕਸ਼ਨਾਂ: 20, 35 ਅਤੇ 50 ਕਿਲੋ ਪਾਸਕਲ ਨੂੰ ਤਜਰਬਾ ਖੇਤਰ ਵਿੱਚ ਤਿੰਨ ਡੂੰਘਾਈਆਂ 20, 30 ਅਤੇ 40 ਸੈਂ.ਮੀ. ਨੂੰ ਕੰਟਰੋਲ (ਕਿਸਾਨਾਂ ਦੇ ਤਜਰਬੇ) ਨਾਲੋਂ ਫਰਕ ਵੇਖਣ ਲਈ ਆਰ.ਸੀ.ਬੀ.ਡੀ. ਡਿਜ਼ਾਇਨ ਵਿਧੀ ਤਹਿਤ ਤਿੰਨ ਵਾਰ ਦੁਹਰਾਇਆ ਗਿਆ। ਦੋ ਸਾਲਾਂ ਦੇ ਅੰਕੜੇ ਪੂਰ ਕਰਨ ਤੇ ਪਤਾ ਲੱਗਾ ਕਿ $S_{20}D_{20}$ ਅਤੇ $S_{35}D_{20}$ ਉਪਚਾਰਾਂ ਵਿੱਚ 82 ਅਤੇ 86 ਪ੍ਰਤੀਸ਼ਤ ਵਿਕਰੀਯੋਗ ਆਲੂਆਂ ਦਾ ਝਾੜ ਵੱਧ ਸੀ। ਪਾਣੀ ਦੀ ਸੁਚੱਜੀ ਕਾਰਜ ਸਮਰੱਥਾ (WUE) ਉਪਚਾਰ $S_{35}D_{20}$ ਵਿੱਚ 177 ਫੀਸਦੀ ਕੰਟਰੋਲ ਨਾਲੋਂ ਵੱਧ ਸੀ। ਆਲੂਆਂ ਦੇ ਸੁੱਕੇ ਮਾਦੇ ਦਾ ਝਾੜ ਵੀ $S_{35}D_{20}$ ਵਿੱਚ ਵਧੇਰੇ ਪਾਇਆ ਗਿਆ। ਇਸ ਤਰ੍ਹਾਂ ਦੋ ਸਾਲਾਂ ਦੇ ਪੂਰਨ ਅੰਕੜਿਆਂ ਤੋਂ ਪਤਾ ਲੱਗਾ ਕਿ ਆਲੂਆਂ ਦਾ ਵਿਕਰੀਯੋਗ ਅਤੇ ਆਕਾਰ ਅਧਾਰਿਤ ਝਾੜ, ਆਲੂਆਂ ਦਾ ਔਸਤਨ ਭਾਰ, ਜੜ੍ਹਾਂ ਦੇ ਸੁੱਕੇ ਮਾਦੇ, ਸਟਾਰਚ ਅਤੇ ਪ੍ਰੋਟੀਨ ਦੀ ਮਿਕਦਾਰ, ਪੁਟਾਈ ਸਮੇਂ ਪੌਦਿਆਂ ਦੀ ਉਚਾਈ, 30, 60 ਦਿਨਾਂ ਮਗਰੋਂ ਅਤੇ ਅਤੇ ਪੁਟਾਈ ਸਮੇਂ ਪੌਦਿਆਂ ਦੇ ਉਪਰਲੇ ਹਿੱਸੇ ਦਾ ਸੁੱਕਾ ਮਾਦਾ $S_{20}D_{20}$ ਅਤੇ $S_{35}D_{20}$ ਵਿੱਚ ਵਧੇਰੇ ਪਾਏ ਗਏ ਜਦੋਂ ਕਿ ਖਰਾਬ ਆਲੂਆਂ ਅਤੇ ਰਡਿਉਸਿੰਗ ਸ਼ੂਗਰ ਦੀ ਮਿਕਦਾਰ ਘੱਟ ਪਾਈ ਗਈ। ਦੋ ਸਾਲਾਂ ਦੀ ਔਸਤਨ ਸੰਖਿਆ ਤੋਂ ਪਤਾ ਲੱਗਿਆ ਕਿ ਉਪਚਾਰ $S_{35}D_{20}$ ਵਿੱਚ WUE ਅਤੇ WUEi, ਕੰਟਰੋਲ ਤੋਂ ਲਗਭਗ ਦੁਗਣੀ ਸੀ ਅਤੇ ਇਸ ਉਪਚਾਰ ਵਿੱਚ ਵਿਕਰੀਯੋਗ ਆਲੂ ਦਾ ਝਾੜ ਵੱਧ ਹੋਣ ਦੇ ਨਾਲ ਨਾਲ 49% ਪਾਣੀ ਦੀ ਬਚਤ ਵੀ ਹੋਈ। ਇਸ ਤੋਂ ਇਹ ਤੱਥ ਸਾਹਮਣੇ ਆਏ ਕਿ $S_{35}D_{20}$ ਉਪਚਾਰ ਸਭ ਤੋਂ ਵਧੀਆ ਸੀ। ਤਜਰਬਾ-II ਦੌਰਾਨ $S_{35}D_{20}$ ਦਾ ਮੌਸਮ ਅਧਾਰਿਤ ਪਾਣੀ ਲਗਾਉਣ ਦੇ ਤਰੀਕੇ ਨਾਲ ਦੋ ਵੱਖ-ਵੱਖ ਵੱਟ-ਖਾਲ (M_1) ਅਤੇ ਬੈਂਡ ਖਾਲ (M_2) ਵਿਧੀਆਂ ਰਾਹੀਂ ਸਾਲ 2012-13 ਅਤੇ 2013-14 ਦੌਰਾਨ ਤੁਲਨਾਤਮਕ ਅਧਿਐਨ ਕੀਤਾ ਗਿਆ। ਬੈਂਡ ਖਾਲ ਵਿੱਚ ਬੈਂਡ ਉਪਰ ਆਲੂ ਦੀਆਂ ਦੋ ਕਤਾਰਾਂ ਲਗਾਈਆਂ ਗਈਆਂ। ਇਸ ਤਜਰਬੇ ਨੂੰ ਸਪਲਿੱਟ ਪਲਾਟ ਡਿਜ਼ਾਇਨ ਵਿਧੀ ਤਹਿਤ ਚਾਰ ਵਾਰ ਦੁਹਰਾਇਆ ਗਿਆ। ਤਜਰਬੇ ਦੌਰਾਨ ਵੱਟ-ਖਾਲ (M_1) ਅਤੇ ਬੈਂਡ ਖਾਲ (M_2) ਵਿੱਚ ਪੰਜ ਉਪਚਾਰਾਂ - I_1 : ਆਈ.ਡਬਲਯੂ.ਸੀ.ਪੀ. ਅਨੁਪਾਤ 1, I_2 : ਆਈ.ਡਬਲਯੂ.ਸੀ.ਪੀ. ਅਨੁਪਾਤ 1.25, I_3 : ਆਈ.ਡਬਲਯੂ.ਸੀ.ਪੀ. ਅਨੁਪਾਤ 1.50, I_4 : $S_{35}D_{20}$ ਅਤੇ I_5 : ਕੰਟਰੋਲ (ਕਿਸਾਨਾਂ ਦਾ ਤਜਰਬਾ) ਰਾਹੀਂ ਪਰਖਿਆ ਗਿਆ। ਵੱਟ ਖਾਲ ਪ੍ਰਣਾਲੀ ਵਿੱਚ ਪਾਣੀ ਦੀ ਸੁਚੱਜੀ ਕਾਰਜ ਸਮਰੱਥਾ, ਆਲੂਆਂ ਦੇ ਔਸਤਨ ਭਾਰ, ਵਿਕਰੀਯੋਗ ਆਲੂ ਅਤੇ ਵੱਡੇ ਅਤੇ ਦਰਮਿਆਨੇ ਅਕਾਰਾਂ ਦੇ ਆਲੂਆਂ ਦਾ ਝਾੜ, ਪੌਦਿਆਂ ਦੀ 60, 75 ਦਿਨਾਂ ਮਗਰੋਂ ਅਤੇ ਪੁਟਾਈ ਸਮੇਂ ਉਚਾਈ ਅਤੇ ਪੁਟਾਈ ਸਮੇਂ ਸੁੱਕੇ ਮਾਦੇ ਦੀ ਮਿਕਦਾਰ, ਬੈਂਡ ਖਾਲ ਪ੍ਰਣਾਲੀ ਤੋਂ ਵਧੇਰੇ ਸੀ। ਕੰਟਰੋਲ ਦੇ ਮੁਕਾਬਲੇ ਉਪਚਾਰ $S_{35}D_{20}$ ਵਿੱਚ ਪਾਣੀ ਦੀ ਸੁਚੱਜੀ ਕਾਰਜ ਸਮਰੱਥਾ ਲਗਭਗ ਤਿੰਨ ਗੁਣਾ ਵਧੇਰੇ ਪਾਈ ਗਈ। $S_{35}D_{20}$ ਉਪਚਾਰ ਵਿੱਚ ਪੌਦਿਆਂ ਦੀ ਉਚਾਈ, 60 ਦਿਨਾਂ ਮਗਰੋਂ ਅਤੇ ਪੁਟਾਈ ਸਮੇਂ ਪੌਦਿਆਂ ਦੇ ਉਪਰਲੇ ਹਿੱਸੇ ਦਾ ਸੁੱਕਾ ਮਾਦਾ, ਆਲੂਆਂ ਦਾ ਅਕਾਰ ਅਧਾਰਿਤ ਅਤੇ ਵਿਕਰੀਯੋਗ ਝਾੜ, ਸਟਾਰਚ ਅਤੇ ਪ੍ਰੋਟੀਨ ਦੀ ਮਾਤਰਾ ਵਧੇਰੇ ਸਨ ਅਤੇ ਖਰਾਬ ਆਲੂਆਂ ਦੀ ਮਾਤਰਾ ਘੱਟ ਸੀ। ਦੋਨਾਂ ਤਜਰਬਿਆਂ ਤੋਂ ਪਤਾ ਚੱਲਿਆ ਕਿ ਵੱਟ-ਖਾਲ ਵਿਧੀ ਰਾਹੀਂ ਆਲੂਆਂ ਨੂੰ ਪਾਣੀ ਲਗਾਉਣ ਲਈ 20 ਸੈ.ਮੀ. ਡੂੰਘਾਈ ਤੇ -35 ਕਿਲੋ ਪਾਸਕਲ ਮਿੱਟੀ ਦੀ ਮੈਟ੍ਰਿਕ ਸਮਰੱਥਾ ਤੇ ਟੈਂਸੀਓਮੀਟਰ ਦੀ ਵਰਤੋਂ ਵਧੇਰੇ ਕਾਰਗਰ ਸੀ। ਇਸ ਵਿਧੀ ਰਾਹੀਂ ਪਾਣੀ ਲਗਾਉਣ ਨਾਲ 45-45.5 ਮਿ.ਮੀ. (ਵਰਖਾ ਨੂੰ ਧਿਆਨ ਵਿੱਚ ਰੱਖਦੇ ਹੋਏ) ਦੇ 3 ਤੋਂ 4 ਪਾਣੀ ਲੱਗ ਸਕਦੇ ਹਨ। ਇਸ ਤੋਂ ਇਲਾਵਾ ਪੌਦਿਆਂ ਨੂੰ ਪੁੰਗਰਾਉਣ ਲਈ 50 ਮਿ.ਮੀ. ਦੇ ਵਧੀਕ 2 ਪਾਣੀ ਜਿਹਨਾਂ ਵਿੱਚੋਂ ਇੱਕ ਬਿਜਾਈ ਤੋਂ ਪਹਿਲਾਂ ਅਤੇ ਇੱਕ ਬਿਜਾਈ ਤੋਂ ਬਾਅਦ ਲਗਾਏ ਗਏ ਸਨ। ਮੌਜੂਦਾ ਅਧਿਐਨ ਤੋਂ ਇਹ ਤੱਥ ਸਾਹਮਣੇ ਆਏ ਕਿ ਇੱਕ ਪਾਣੀ ਪੌਦਿਆਂ ਦੇ ਪੁੰਗਰਨ ਤੋਂ 2 ਹਫ਼ਤਿਆਂ ਮਗਰੋਂ ਅਤੇ ਬਾਕੀ 2-3 ਪਾਣੀ 17 ਦਿਨਾਂ ਦੇ ਵਕਫੇ ਤੇ ਕਿਸਾਨਾਂ ਦੁਆਰਾ ਵਰਤੇ ਜਾਣ ਵਾਲੇ ਤਰੀਕੇ ਨਾਲੋਂ ਵਧੇਰੇ ਪਾਣੀ ਦੀ ਬਚਤ ਕਰਦੇ ਹਨ।

ਮੱਖ ਸ਼ਬਦ: ਵੱਟ-ਖਾਲ ਸਿੰਚਾਈ ਪ੍ਰਣਾਲੀ, ਵਿਕਰੀਯੋਗ ਆਲੂਆਂ ਦਾ ਝਾੜ, ਆਲੂ, ਮਿੱਟੀ ਪਾਣੀ ਤਨਾਅ, ਆਲੂਆਂ ਦਾ ਔਸਤਨ ਭਾਰ, ਪਾਣੀ ਦੀ ਸੁਚੱਜੀ ਕਾਰਜ ਸਮਰੱਥਾ

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CHAPTER I

INTRODUCTION

Potato (*Solanum tuberosum* L.) is an economically important staple crop in both developed and developing countries, with an annual global production of about 376.45 million tonnes (<http://faostat3.fao.org/> 2013). Globally, it is the fourth largest food crop after wheat, rice and maize in terms of production. The potato cropping area has been expanding in developing countries of particularly in Asia and Africa (Haverkort *et al* 2004). The most rapid annual potato market growth (3.8%) is expected in India (Guenthner 2010). There is potential for processed potato market growth in developing countries like India. While global processed potato demand is likely to expand, fresh potatoes will continue to be the main usage. This expansion is opening new cropping areas in some environments that could be negatively affected by global warming (Thiele *et al* 2010). A reduction of 18–32% of potato global yield caused by climate change is projected to occur during 2010-2039 (Hijmans 2003). Alongside temperature and atmospheric CO₂ increases, climate change will bring about a larger rainfall variability and evaporative demand (Kundzewicz *et al* 2007), a situation that will affect potato, which is a drought sensitive crop (van Loon, 1981). Furthermore, competing water use for agriculture and other activities is becoming an important issue worldwide (Naylor 2009). Under these unpredictable and highly variable conditions, increasing water use efficiency (WUE) by irrigated potato crops is an important objective. Water economy should always guide agriculture practices, WUE is the main trait used to evaluate water economy (Jones, 2004). Improvement in WUE has typically been interpreted as increased beneficial use of diverted water for irrigated agriculture or the “More crop per drop; same crop less drop.

Worldwide, irrigation systems have become more and more accessible, and water is often the cheapest available resource for improving yield, cheaper than, for instance, fertilizers and pesticides (Savic *et al* 2011). Thus, more and more crops and fields are irrigated, thanks to which yield can be increased without increasing land dedicated to agriculture—indeed, about 20% of worldwide agricultural land is irrigated, generating 40% of food production (Garcez-Restrepo *et al* 2007). However, due to global restriction in fresh water resources, irrigation strategies that have higher water productivity should be adopted in order to save the water resources and improve crop production (Ahmadi *et al* 2014).

Potato has historically contributed to the food and nutrition security. It can supplement the food needs of the country in a substantial manner as it produces well balanced protein and higher calories per unit area and per unit time than any other major food crop. Potato is one of the most important crops in India with the present production of 45 million tonne from 1.90 million ha area (<http://faostat3.fao.org/> 2013). Wider adaptability in planting

and shorter life span of potato makes it an ideal crop under intensive cropping system in most of agro-climatic conditions. Potato has emerged as an important food crop grown as a cool, dry-season (winter) irrigated crop on the Indo-Gangetic plains following an expansion in irrigation infrastructure and the construction of large cold-storage facilities for storing potato before sale and as a seed crop during summer (Bardhan Roy *et al* 1999). India's potato production has noticed a phenomenal increase (about 20 times) since 1950s, mainly due to strong demand from the processing industry and attractive returns. During the last 58 years, overall potato yield grew at the rate of 1.5 per cent at national level. After achieving spectacular growth during the seventies, the yield growth started to decline and in the recent past it became negative (Pandit and Chandran 2011). Looking at the estimated demand of nearly 50 million tonnes of potato by 2020 for nearly 1.3 billion population, the production and productivity needs to be increased. The average yield of potato in India was 23.7 tonne/ha during 2010-11 (<http://faostat3.fao.org/> 2013) and the corresponding value for the state of Punjab was 25 tonne per/ha (Anonymous 2013a). However, it can yield up to 40-50 tonne/ha and it is amongst the most promising crops, particularly for areas of high human population density like Asia (Chadha and Grewal 1993). However, the potential yield is quite high and the gap between potential yield and realizable yields can be minimized by generation and application of improved production and protection technologies.

In Punjab, there has been an over-exploitation of groundwater resources (Hira 2009). The intensive irrigation may soon become uneconomic. Additionally, the water scarcities in agriculture are being projected in the light of agriculture, climate change and competition from non agriculture sectors. There is an increased pressure on the availability of water for agricultural sectors as the demand for water in industrial as well as domestic sectors is increasing day-by-day. However, keeping in view the increasing area under potato crop, owing to its ever increasing demand and higher production per unit area and time, there is a need for evaluating accurate irrigation scheduling to improve irrigation water use and energy use efficiency (Gulati and Singh, 2011).

Potato is a shallow-rooted and cool-season crop, and its yield is highest when average daytime temperatures are about 21° C. Cool night temperatures are critical for the accumulation of carbohydrates and dry matter in the tubers (Belanger *et al* 2000). Unlike other crops, the economic product here is not exposed to the free atmosphere, but develops inside the soil. The yield of potato is determined by accumulation of tuber for nearly 1.5 to 2 months. Variation in any of the soil moisture, soil aeration and soil temperature affects the yield considerably. In the North-Western India, potato is mainly grown in winter, which receives little rainfall. Being shallow rooted crop it can not be sustained on the moisture stored in the soil in the preceding monsoon. It seems to be most frequently irrigated crop

among the major *rabi* season crops in Punjab. It requires 7-8 light irrigations for higher productivity under Punjab Conditions (Anonymous 2013b). Prevailing over a growing season the water requirement of potato varies between 350 to 500 mm, depending on environmental conditions, soil type and cultivar (Sood and Singh, 2003). The crop prefers wet moisture regime not only for adequate moisture owing to its shallow root system but also for the maintenance of low soil strength, which are conducive for the development and enlargement of tubers (Prihar and Sandhu 1987).

Surface irrigation methods are utilized in irrigated lands yet its field level application efficiency is often 40-50% (Von Westarp *et al* 2004). Furrow irrigation is the most prevalent method of irrigation to potato under north Indian conditions, although, this method results in considerable loss of water by deep percolation below the root zone besides the conveyance loss during water distribution. The furrows have a uniform and gentle slope down their length. To achieve it, land is carefully levelled and graded with plankers. Water is never allowed to overflow the ridges as this may seal the soil pores, thereby raising its bulk density leading to anaerobic conditions (Sood and Singh 2003). Such adverse effects result in seed tuber decay especially when soil temperature is high at planting. The ridges may be wetted only upto two third of height leaving the rest to be moistened gradually by capillary movement of water. Fisher (1995) suggested that by using beds, irrigation application could be reduced if applied evenly. Double row planting of tubers resulted in significantly higher number of branches and tubers per plant, foliage coverage and highest tuber yield in addition to higher water-use efficiency as compared to single row planting on the ridge (Panigrahi *et al* 2001). Although not always statistically significant, water use efficiency was greater in all years for the altered bed shapes (flat-topped hill, wide-bed hill) compared to the standard hill geometry (Harms and Korschuh 2010). Greater water use efficiency can be interpreted as more of the applied water infiltrated into the hill, where the potato plant could use it for transpiration and tuber development. Greater marketable yield, increased number of marketable tubers, and reduced tuber deformities resulted with the altered hill shapes. Drip irrigation saves water and nutrients. But, the drip irrigation system is costly to install and manage for potato cultivation and growers are reluctant to install on their fields, where capital has already been spent to install furrow irrigation system or/and canal water is cheaply available for irrigation purposes (Singh *et al* 2010).

Precise scheduling of irrigation water applications leads to resource conservation, environmental and production benefits. Soil physical properties (texture and structure) and soil water and nutrient content affect root growth (Ahmadi 2010). Potatoes have a shallow root system which requires more frequent irrigations compared to other crops. Many irrigation experiments have shown that potato is relatively sensitive to moisture stress (Opena

and Porter 1999, Fabeiro *et al* 2001) because it has a sparse root system and approximately 85 per cent of the root length is concentrated in the upper 0.3 m soil layer (Opena and Porter 1999, Iwama 2008). However, under field conditions the basal and the junction roots do not appear to transport water to the tuber. The stolon and the tuber roots, on the other hand, transport water to the tubers under similar moisture conditions (Kratzke and Palta 1985). Due to the sparse and shallow root system, potato is sensitive to drought stress and tuber yield might be reduced considerably in response to soil moisture deficits. Therefore, efficient and sustainable irrigation is needed to secure high yield and quality of tuber production but critical to reaching this goal in many regions will be access to an adequate water supply.

The irrigation water requirement of a crop in the field is a function of cultural practices, climatic demand and soil type. So, the optimum irrigation varies from one location to another, depending on the agroclimatic conditions. Similar amounts of soil water may not be equally important in differently textured soils, being more in coarse and medium textured soils than in fine textured soils. The fixed day interval criterion of scheduling irrigation to potato may not be feasible in more erratic climatic conditions being faced during the present time. This, in general leads to over application of irrigation water to the crop. Farmers in their anxiety for higher yield, apply water either heavily or frequently at an interval of 2 to 7 days. In either of the cases, there is excess application of water, most of which is lost as deep percolation along with some soil nutrients besides creating soil aeration and soil temperature problems. There is thus need to optimize more precise technique of scheduling irrigation to potato. Moisture stress, depending on the crop growth stage can reduce tuber yields, produce misshapen tubers, and or adversely affect the quality of table and processing potatoes. The malformed tubers are often caused by widely varying soil moisture conditions. The quality characters of potatoes are optimized under proper soil moisture conditions. The incidence of green and blemished tubers was reduced and the protein concentration was increased under the completely mulched with ridge planting of potatoes (Qin *et al* 2014) Apart from it insufficient or excessive irrigation can result in reduced yields, reduced specific gravity and increased incidence of tuber defects such as second growth, hollow heart, *Sclerotium* rot, bacterial wilt, *Verticillium* wilt, *Fusarium* wilt, powdery scab and soft rot etc.. The late blight incidence in tubers is greatly encouraged by prolonged excess soil water conditions. Soft rot is a problem promoted by high moisture coupled with high temperature conditions. Water management, besides influencing the incidence of diseases in potato has also special significance in pest management. The moist soil conditions reduce the formation of cracks in the soil that are otherwise conducive to the entry of potato tuber moth and its larvae (Sood and Singh 2003). Excessive irrigation will also increase production costs through leaching of

fertilizers and higher pumping costs. The accurate irrigation scheduling can minimize these problems.

There are several options for precise irrigation scheduling (Shock and Wang 2011). One option is to schedule irrigations based on estimated crop evapotranspiration and replace the consumptive water use. In weather-based scheduling, the decision to irrigate relies on the soil water balance. The water balance technique involves determining the change in soil moisture over time. A second option is to measure plant water stress and irrigate according to known plant yield and quality responses to water stress. Plant water stress can be measured either by the negative water potential in plant tissues or by the incremental heating of the crop canopy resulting from water stress. Irrigation based on soil moisture content requires a method by which soil moisture status can be measured in the field. Perhaps the simplest and most common method is the “feel method,” where irrigation is initiated when the soil “feels” dry (Maynard and Hochmuth, 2007). The real breakthrough in irrigation scheduling was made when the field studies based on the soil water regime concept were conducted.

Other irrigation scheduling options rely on the measurement of soil water content or soil water tension. Soil water content can be determined through gravimetric, neutron probe, time domain reflectometry, or capacitance probe measurements. Measurements of soil water content can be particularly useful when soils are very uniform over large geographic expanses or uniform in nursery container mixes. Measurements of SWT can be determined with tensiometers, gypsum blocks, heat dissipation sensors, granular matrix sensors, psychrometers, and other devices. Measurements of SWT are particularly useful for irrigation scheduling when a SWT irrigation criterion that maximizes crop performance is determined for a given crop in a particular environment. When a SWT irrigation criterion is coupled with knowledge of the soil water holding capacity, a planned increment of water can be applied at the right time, reducing the off-site effects of water movement. Thus, soil water tension is closely related to plant stress, and crop yield and quality are closely related to SWT irrigation criteria (Shock *et al* 2007). Tensiometer is one of the sophisticated instruments to determine soil moisture by measuring soil matric potential which represents the force necessary for plant roots to remove water from small pores in the soil. A tensiometer is a sealed, water-filled device that exchanges water with the soil through a porcelain cup (Hubbell and Sisson 2003). As plants remove water from the soil, water is drawn from the porcelain cup, developing a partial vacuum in the tensiometers. The partial vacuum is registered as kPa [kPa = centibars (cbar)] of soil water tension on a mechanical gauge or through an electronic output device. Tensiometers provide a direct measurement (the physical force that plants exert removing water from the soil) of soil water tension from 0 to 85 kPa. Tensiometers do not require site-specific calibrations. These last for many years and they can be repaired (Shock and Wang

2011). Soil matrix potential-the force with which water is held in soil matrix, has been successfully used as a basis for scheduling irrigation to rice crop in Punjab (Kukul *et al* 2005) with 25-30 per cent saving in irrigation water. This technique actually measures the soil water availability to crop plants, which takes into account the soil texture as well as atmospheric demand for water, thereby indicating plant water availability in the soil. However, previous studies in the region have mostly used weather based scheduling, an indirect approach to evaluating soil water availability for the plants and not SWT/soil matrix potential for irrigation scheduling to potato (Kumar *et al* 2009, Singh *et al* 2010, Singh *et al* 2012, Tyagi *et al* 2012, Singh and Sood, 2013, Verma *et al* 2013).

Thus a study was conducted during 2011-13 for “Optimizing soil matrix potential and climate based irrigation scheduling to potato under different establishment methods” with the objectives to optimize the most suitable soil matrix potential value and its depth of measurement for scheduling soil matrix potential based irrigation to potato as well as to study the soil water dynamics and crop performance with optimum soil matrix potential and climate based irrigation scheduling.

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CHAPTER II

REVIEW OF LITERATURE

Different irrigation scheduling methods have been used under various climatic conditions for improving productivity of potato, saving irrigation water and improving crop yield and water use efficiency.

A. Effect of Irrigation scheduling on the tuber yield of potato:

Several options are available for precise irrigation scheduling to crops (Shock and Wang, 2011). One option is to schedule irrigations based on estimated crop evapotranspiration and replace the consumptive water use. A second option is to measure plant water stress and irrigate according to known plant yield and quality responses to water stress. Other irrigation scheduling options rely on the measurement of soil water content or soil water tension (SWT). When a soil water tension irrigation criterion is combined with the knowledge of the soil water holding capacity, a planned increment of water can be applied at the right time, reducing the off-site effects of water movement. Tensiometer is an instrument used to determine soil moisture status by measuring soil matric potential (SMP). It symbolizes the force necessary for plant roots to extract water from the soil (Shock and Wang, 2011).

Numerous studies using tensiometers to measure SMP and for scheduling irrigation to potato have been reported: irrigation scheduling based on crop water stress index of 0.2 by using SMP of 30 kPa at 0.3 m depth in surface drip irrigation utilized 167 mm, and subsurface drip irrigation based on SMP of 30 kPa used 129 mm of irrigation water in a sandy loam soil of north Dakota for Russet Burbank potatoes (Shae *et al* 1999). While, Bush *et al* (2000) made an investigation with the objective to compare the effect of cyclic and tensiometric irrigation methods on growth of lantana (*Lantana camara*). Low-tension switch tensiometers were compared to schedule overhead [one time a day (1×) at 0600 and cyclic irrigation three times a day (3×) at 0600, 1200, and 1800] for the production of 1-gallon lantana plants. Three low-tension tensiometers (1/block) were set at 7 cb and allowed to irrigate over a 12-hour period. Three separate planting dates occurred and then terminated after ~7 weeks. Tensiometric irrigation increased root and shoot growth compared to scheduled irrigation for the 24 May 1999 harvest date. Cyclic irrigation produced plants with shoot and total root weights >1× and tensiometer treatments for the September harvest date. Tensiometers sharply reduced irrigation requirements compared to scheduled irrigation volume by at least 50% of the 1× and 3× treatments weekly.

Kang *et al* (2004) conducted a field experiment comparing different irrigation frequencies and SMP thresholds on potato evapotranspiration (ET), yield (Y) and water-use

efficiency (WUE) in a loam soil. The experiment included five treatments for soil matric potential: F1 (-15 kPa), F2 (-25 kPa), F3 (-35 kPa), F4 (-45 kPa) and F5 (-55 kPa) and six treatments for irrigation frequency: N1 (once every day), N2 (once every 2 days), N3 (once every 3 days), N4 (once every 4 days), N6 (once every 6 days) and N8 (once every 8 days). Results indicated that both soil matric potential and drip irrigation frequency influenced potato ET, Y and WUE. Potato Y and WUE were found to increase as irrigation frequency increased. Potato Y increased with an increase in soil water potential then started to decrease. The highest Y and WUE values were achieved with a soil matric potential threshold of -25 kPa and an irrigation frequency of once a day.

Wang *et al* (2007) conducted study on the effects of soil matric potential (SMP) on potato growth under drip irrigation in the North China Plain and concluded that in terms of potato growth, water use efficiency and I_{WUE} , an SMP of -25 kPa was most favourable for potato production, while an SMP of -15 kPa was too high and an SMP of -45 kPa or more leads to notable water stress. The mercury column tensiometers showed the most dramatic changes occurred within 20 cm horizontal distance from the plants and within 30 cm of the soil surface. They found placement at 20 cm right under the emitter was best in characterizing soil water status by measuring SMP. This research confirmed the difficulty of obtaining high tuber yields in semiarid areas without adequate water supply. Root weight density had a tendency to increase gradually as SMP dropped from -15 to -35 kPa in 0–30 cm soil layer, reaching a maximum in F3 and then declining as SMP decreased from -35 to -55 kPa. It was also found that the tuber bulking rate was most sensitive to water stress during the middle growth period, and that a SMP of -45 kPa or lower would lead to a sharp reduction in the tuber bulking rate. Marketable tuber weight per plant (Tuber weight - 50 g) was significantly affected by soil matric potential.

Wang *et al* (2011) reported that highest WUE, and yield was obtained with -25 kPa soil matric potential during tuber initiation and growth and -35 kPa during tuber maturation. Analysis of plant height, tuber yield and WUE showed that a drip irrigation threshold of -35 kPa SMP led to obvious water stress for potato growth in the arid area. Thus, drip irrigation threshold of -35 kPa SMP at all growth stages caused water stress for potato growth and development in the arid area.

Carli *et al* (2014) evaluated the effects of different irrigation regimes on ten potato clones in the lowlands of Tashkent, Uzbekistan, during the summer cropping season (July–October) of three consecutive years (2008, 2009 and 2010). The applicability of a growth model to predict yield under the different water regimes was tested. The control (T_1) represented optimal irrigation conditions. Irrigation was monitored based on soil water potential (Ψ_{soil}) which was measured in each treatment using granular matrix sensors placed at

30 cm depth every two plots. Data were recorded every day at 2:00 p.m. with a data logger. Irrigation was applied when soil water potential (Ψ_{soil}) dropped to -40 to -45 kPa and cut off when Ψ_{soil} reached -20 kPa. The two other treatments mimicked situations faced by farmers in situations of reduced water availability that often occur during the second growing season and simulated different levels of water depletion, from transient to continuous. In treatment T₂, water was applied as in T₁ up to 40 days after planting (DAP) and there after only at 60 and 80 DAP. In treatment T₃, water was applied as in T₁ only upto 40 DAP and no more water was applied after this date. The significant correlation for tuber yield among treatments suggested that yield under water limitation was driven more by potential yield than water restriction tolerance. Tuber yield was more associated to tuber weight than to tuber number; a component already largely determined when the different water treatments were initiated. The reduction of water supply after tuberization had a limited effect on yield and consequently drastically enhanced water use efficiency.

On reviewing several studies on different crops, Medici *et al* (2014) generalized the statement that irrigated plants should be grown between 10 and 20 kPa SWT to achieve the highest combination of yield and WUE. At the maturity stage, a higher SWT (20–35 kPa) might be advisable to improve fruit quality and WUE without the risk of reducing yield. It was reported by the Medici and his co-workers that there is need for further conducting research on the basis of soil water tension for irrigation scheduling to crops.

Several workers had studied the effect of climate based irrigation scheduling on the potato tuber yield. Kumar *et al* (2007) evaluated the performance of two chipping potato cultivars Kufri Chipsona-1 and Kufri Chipsona-2 under different irrigation levels in sub-tropical conditions of west-central plains (U.P.) during 2002–04. They reported non-significant variation in number of stems and compound leaves with irrigation levels but observed consistent decline in processing grade and total tuber number ha⁻¹ under water stress. Like tuber number, processing-grade tuber yield, total tuber yield, biomass yield and average tuber weight also decreased with decrease in irrigation frequency from 15 mm to 35 mm cumulative pan evaporation (CPE). Efficiency of water use increased linearly (81.1 to 146.4 kg tubers ha-mm⁻¹) in response to water stress.

Kumar *et al* (2009) conducted a study during 2003–04 to compare microsprinkler, drip and furrow irrigation systems for potato (*Solanum tuberosum* L.) production at Central Institute of Post Harvest Engineering and Technology, Abohar, Punjab. They observed that potato tuber yield increased with increasing irrigation level from 0.60 to 1.20 IW:CPE. However, highest water use efficiency (1.37 q/ha-mm) was recorded with 0.80 IW:CPE under microsprinkler irrigation.

Saikia (2011) conducted a field experiment with 4 irrigation schedules viz., irrigation to each furrow at 25 mm CPE (I_1), irrigation to alternate furrow at 25 mm CPE (I_2), irrigation to each furrow at stolon formation (SF) stage (30 DAP), tuber formation (TF) stage (50-55 DAP) and tuber development (TD) stage (65-70 DAP) (I_3), and irrigation to each furrow at stolon formation (SF), tuber formation (TF) and tuber development (TD) stage + 1 extra irrigation after 10 days of irrigation at tuber development stage (I_4) and 2 mulching treatments viz., no mulch (M_1) and mulching with water hyacinth @ 5t/ha (M_2). Tallest plants were recorded when irrigations were applied at SF + TF + TD stage + irrigation after 10 days of TD stage under M_1 condition. Number of shoots/plant was significantly affected by different treatments during both the years. Highest total tuber yield of 14.2 t/ha was recorded when irrigation was applied at each furrow at 25 mm CPE during 2006-07. In case of large size tubers (> 75 g), highest tuber yield (2.21 t/ha) was recorded when irrigation was applied at SF + TF + TD stage + irrigation after 10 days of TD stage under M_1 condition during the same cropping season. Highest water use efficiency (12.63 q/ha cm) was recorded in application of irrigation at stolon formation (SF) + tuber formation (TF) + tuber development (TD) stage under mulch condition during first year while during second year it was highest (7.45 q/ha-cm) in irrigation at 25 mm CPE in each furrow.

Patel *et al* (2011) concluded that for higher number and yield of processing grade A tubers and net return, potato Cv. Kennebec be irrigated with drip irrigation (0.8 Pan Evaporation Fraction) with laterals in each pair of potato rows in light textured soil of North Gujarat. The effect of irrigation methods was significant on number and yield of processing grade 'A' and 'B' tubers. The crop irrigated with drip (0.8 PEF) with lateral in each row was significantly superior over other irrigation treatments, but it was at par with crop irrigated with drip (0.8 PEF) with lateral in each pair.

Ierna *et al* (2011) conducted 2-year experiment with the aim of achieving an appropriate combination of irrigation water and nutrient application in cultivation management of a potato crop in a Mediterranean environment. Their research confirmed the difficulty of obtaining high tuber yields in semiarid areas without adequate water supply. The combined effects of 3 levels of irrigation (irrigation only at plant emergence, 50% and 100% of the maximum evapotranspiration (ETM) and 3 levels of mineral fertilization (low: 50, 25 and 75 kg ha⁻¹, medium: 100, 50 and 150 kg ha⁻¹ and high: 300, 100 and 450 kg ha⁻¹ of N, P₂O₅ and K₂O) to study the effect on the tuber yield and yield components, on both irrigation water and fertilizer productivity and on the plant source/sink (canopy/tubers dry weight) ratio. They found that the treatments based on 50% ETM and a medium level of fertilization represent a valid compromise in early potato cultivation management. Compared to the high

combination levels of irrigation and fertilization, this treatment entailed a negligible reduction in tuber yield to save 90 mm ha⁻¹ year⁻¹ of irrigation water, with notable economic savings for farmers compared to the spendings that were usually made.

Verma *et al* (2012) conducted a field experiment in two consecutive *rabi* and summer seasons (October–July) of 2007-08 and 2008-09 at New Delhi to study the effect of irrigation and nitrogen management on productivity of potato (*Solanum tuberosum* L.) and their residual effect on succeeding maize (*Zea mays* L.). The experiment was laid out in split plot design with two irrigation methods (conventional furrow irrigation and alternate furrow irrigation) and three irrigation regimes (60, 80 and 100 mm CPE) in the main plots and four nitrogen levels (90 kg N through urea + 30 kg N/ha through FYM, 120 kg N/ha through urea, 120 kg N through urea + 30 kg N/ha through FYM and 150 kg N/ ha through urea) in sub-plots with three replications. Results indicated that significantly higher plant height, fresh and dry weight of haulms, fresh and dry weight of tubers/hill, yield of different grade tubers and total tubers were obtained with conventional furrow irrigation as compared with alternate furrow irrigation in rotation. Among the irrigation regimes, irrigation at 60 mm CPE recorded significantly the highest growth characters, yield attributes and total tuber and biological yields over irrigation at 80 and 100 mm CPE.

Ierna and Mauromicale (2012) investigated the effects of four irrigation regimes (irrigation only at plant emergence, irrigation during the whole cycle, irrigation from tuber initiation up to 50% of tuber growth, irrigation from 50% of tuber growth to the end of tuber growth), on the tuber yield and yield components, on irrigation water productivity (IWP) and on tuber quality. The results showed a marked and significant effect of the irrigation regime on average tuber weight, tuber yield, IWP, source/sink relationships and dry matter content of tubers. The source to sink ratio and discarded production was significantly lower for plots with irrigation during the whole cycle and irrigation from tuber initiation up to 50% of tuber growth as compared to irrigation only at plant emergence and irrigation from 50% of tuber growth to the end. They also demonstrated that high yield levels of potatoes, high IWP and good tuber quality can be reached by irrigating with 100% maximum evapotranspiration (ET_m) supply from tuber initiation up to 50% of tuber growth. Compared to irrigation with 100% ET_m supply throughout the whole cycle, which allowed making savings of irrigation water of roughly 77 mm year⁻¹.

The field experiments were conducted during Autumn and *rabi* seasons of two consecutive years *i.e.* 2005-06 and 2006-07 at CPRI Campus, Modipuram, Meerut (UP), on light textured (Typic-Ustrocrept) soils by Singh *et al* (2012) to study the influence of irrigation and mulch on growth, yield and economics of potato. Results revealed that the irrigation given to all furrows with paddy straw mulch @ 5 t ha⁻¹ produced significantly

higher tuber yield (295 q ha^{-1}) as well as tuber numbers ($605 \text{ thousands ha}^{-1}$) in comparison to other treatments tried in main crop season. However, the differences between the yield produced by irrigation applied to all furrows and irrigations given at critical crop growth stages (PE, SF, TI, ETES & LTES) with mulch were non significant. In early crop of potato, the irrigation applied at 20 mm CPE with paddy straw mulch @ 5 t ha^{-1} gave significantly higher total yield (170 q ha^{-1}) than other irrigation treatments.

Tyagi *et al* (2012) conducted a field experiment on sandy loam soil during winter season of 2004-05 and 2005-06 at Indian Agricultural Research Institute, New Delhi. The treatments comprised 5 irrigation levels (irrigation at critical stages of potato (*Solanum tuberosum* L.), irrigation at critical stages of French bean (*Phaseolus vulgaris* L.), and irrigation at 0.8, 1.2 and 1.6 IW/CPE ratio) as main plots and 3 cropping systems (sole potato, sole French bean and potato + French bean in 2:3 row ratio). Irrigation at IW/CPE ratio of 1.6 produced the highest tuber yield followed by irrigation at 1.2 IW/CPE ratio, while the lowest tuber yield was achieved with irrigation at 0.8 IW/CPE ratio. Although the tuber yield with irrigation applied at critical growth stages (CGS) of potato was significantly lower than with IW/CPE ratio of 1.6, but the water use efficiency (WUE) with CGS of potato was higher.

The other workers have made studies on the effect of deficit irrigation scheduling on yield of potato. Shock *et al* (1998) applied deficit irrigation at accumulated E_t ranging from 50 to 100%. They reported that irrigation tuber yield decreased with decrease in applied water in the year 1992. In 1994, all cultivars showed linear increase in both total and U.S. No. 1 yield with increase in water applied. Average over the three year, cultivar Umatilla Russet had a high regression coefficient for applied water vs. U.S. No. 1 yield and was the most productive of U.S. No.1 yield. Potato cultivar Russet Burbank and Umatilla Russet were the most productive in total yield when irrigated at full E_t .

Onder *et al* (2005) conducted research during the spring seasons of 2000 and 2002 in Hatay province located in the East Mediterranean Region of Turkey. The research investigated the effects of two drip irrigation methods (surface drip: SD and subsurface drip: SSD) and four different water stress levels on potato yield and yield components. The levels were full irrigation (I_{100}), 66% of full irrigation (I_{66}), 33% of full irrigation (I_{33}) and un-irrigated (I_0) treatments. Five and three irrigation were applied in 2000 and 2002 early potato growing seasons, respectively. Total irrigation amount changed from 102 to 302 mm and from 88 to 268 mm in 2000 and 2002, respectively. Irrigation levels resulted in significant difference in both years on yield and its components. Water stress significantly affected the yield and yield parameters of early potato production. In 2000, the mean tuber weight increased with increasing water amount under both irrigation methods. The highest mean tuber weight was obtained from I_{66} treatment for both irrigation methods in 2002. Un-irrigated

treatment gave the lowest values for yield parameters except smaller size (28–45 mm) total tuber yield, and yield reductions were 32 and 37% compared to the most yielding treatment in the 2000 and 2002, respectively. In 2000, tuber yield, bigger size and total tuber yield per ha increased with more water amount under both irrigation method. In 2002, the irrigation at 66% level resulted in the highest tuber yield values except 28–45 mm size tuber yield under both irrigation method, and there were significant reductions on total yield when applying more water. Water deficiency more than 33% of the irrigation requirement could not be suggested. Treatment I₃₃ (66% deficit) gave maximum irrigation water use efficiency (IWUE) for both years. The IWUE ranged from 99.1 to 309.0 kg ha⁻¹ mm⁻¹ which was calculated as ratio of yield to irrigation amount, while TWUE ranged from 65.7 to 114.3 kg ha⁻¹ mm⁻¹ which was calculated as ratio of yield to evapotranspiration.

Unlu *et al* (2006) conducted field experiments in the in the Nigde-Nevsehir (arid) region on a Fluvents (Entisols) soil to determine water and nitrogen requirements of potato crops under sprinkler and trickle irrigation methods. Irrigation treatments were based on Class A pan evaporation and nitrogen levels were formed with different nitrogen concentrations. There were four nitrogen levels: N₀: 0 gm⁻³, N₁: 30 gm⁻³, N₂: 45 gm⁻³, N₃: 60 gm⁻³ and two irrigation water levels: $k_{cp1} = 0.8E_p$ and $k_{cp2} = 1.2E_p$ where water applications were 0.8 and 1.2 times of cumulative pan evaporation measured within the irrigation interval of 7 days using a standard Class A pan for trickle irrigation, while irrigation level was $k_{cp2} = 1.2E_p$ for sprinkler irrigation method. The highest yield was measured in sprinkler-irrigated plots at the 60 g m⁻³ nitrogen concentration level in the irrigation treatment with limited irrigation (480 mm). Statistically higher tuber yields were obtained at the 45 and 60 g m⁻³ nitrogen concentration levels in irrigation treatments with full and limited irrigation. Maximum yields were obtained with about 17% less water in the sprinkler method as compared to the trickle method (not statistically significant). On the loam and sandy loam soils, tuber yields were reduced by deficit irrigation corresponding to 70% and 74% of evapotranspiration in sprinkler and trickle irrigations, respectively. Water use of the potato crop ranged from 490 to 760 mm for sprinkler-irrigated plots and 565–830 mm for trickle irrigated treatments. The highest water use efficiency (WUE) levels of 7.37 and 4.79 kg m⁻³ were obtained in sprinkle and trickle irrigated plots, respectively. There were inverse effects of irrigation and nitrogen levels on the WUE of the potato crops. Significant linear relationships were found between tuber yield and water use for both irrigation methods.

Ahmadi *et al* (2010) investigated yield and water productivity of potatoes grown in 4.32 m² lysimeters coarse sand, loamy sand, and sandy loam and imposed to full (FI), deficit (DI), and partial root-zone drying (PRD) irrigation strategies. PRD and DI as water-saving irrigation treatments received 65% of FI after tuber bulking and lasted for 6 weeks until final

harvest. Analysis across the soil textures showed that fresh yields were not significant between the irrigation treatments. However, the same analysis across the irrigation treatments revealed that the effect of soil texture was significant on the fresh yield and loamy sand produced significantly higher fresh yield than the other two soils. More analysis showed that there was a significant interaction between the irrigation treatments and soil textures that the highest fresh yield was obtained under FI in loamy sand. Furthermore, analysis across the soil textures showed that water productivities, WP (kg ha^{-1} fresh tuber yield mm^{-1} ET) were not significantly different between the irrigation treatments. However, across the irrigation treatments, the soil textures were significantly different. This showed that the interaction between irrigation treatments and soil textures was significant that the highest significant WP was obtained under DI in sandy loam. While PRD and DI treatments increased WP in coarse sand and in sandy loam relative to FI, they decreased WP in loamy sand by 15 and 13%. The reduced WP in loamy sand was due to nearly 28% fresh tuber yield loss in PRD and DI relative to FI even though ET was reduced by 9 and 11% in these irrigation treatments.

Two field experiments were conducted in two semi-arid areas in northern China to test the response of three potato varieties to supplemental irrigation (Xie *et al.* 2012). Conventional furrow irrigation was compared to the partial root-zone drying (PRD) irrigation system at different watering levels, with and without plastic mulching. PRD₅₀ (A total of 2000 m^3/ha of water applied to each furrowed plot, furrows alternately watered at each irrigation) produced similar ($P > 0.05$) yields to conventional irrigation at both C₁₀₀ (A total of 4000 m^3/ha of water applied to each furrowed plot) and C₅₀ (A total of 2000 m^3/ha of water applied to each furrowed plot) levels in both Hohhot and Lanzhou sites. C₅₀, produced similar yields to C₁₀₀ in Lanzhou but significantly less than the control in Hohhot ($P < 0.05$). In both sites, the lowest yields were produced by the PRD₂₅ (A total of 1000 m^3/ha of water applied to each furrowed plot, furrows alternately watered at each irrigation) and the RF (rainfed treatment: no supplemental irrigation to rain) treatments, which did not differ from each other in Hohhot, whereas in Lanzhou the yield caused by the RF treatment was significantly lower. Reducing the supplementary water to one half, under both soil-climate conditions tested, did not affect fresh tuber yield; whereas water use efficiency (WUE) was equally incremented by all the reduced water treatments. When this reduction in the amount of supplementary water was managed through the PRD system, the distribution of moisture in the soil seemed to be improved and the potential evaporation was decreased due to the reduced evaporative surface exposed by PRD.

Demelash (2013) conducted study in North Gondar zone in 2010/2011 to investigate deficit irrigation scheduling on potato yield and yield components. Nine treatment combinations: Irrigation frequency based on Crop wet model output, two modified irrigation

frequency and two deficit irrigations of 25 and 50 per cent. It was found that irrigation scheduling significantly affected yield and some yield components. The highest marketable tuber yields was obtained from 0% deficit irrigation and frequency of F 1-2 days (T9) which was 26.33 t ha⁻¹, whereas 25% deficit irrigation with F 1-2 days frequency (T8) gave 25.68 t ha⁻¹. The lowest marketable yield was 3.4 t ha⁻¹ from T4 treatment. The highest water use efficiency (WUE) were obtained from T7 and T8 which were 6.61 and 5.59 kg mm⁻¹, respectively. Therefore, applying 75% of full irrigation depth throughout the whole growing season with frequency based on Cropwat model scheduling 1-2 days resulted better potato yield and saved significant depth of water which improved WUE.

Eskandari *et al* (2013) evaluated the effects of drip irrigation regimes on potato (*Solanum tuberosum* L.) tuber yield and quality in 2009 and 2010. Experimental factors were the irrigation regimes including: FI, providing 100% of the water requirement of potato; IR1, providing 70% of the water requirement of potato by reducing the applied irrigation water between planting and tuber initiation by 30%; and IR2, providing 70% of the water requirement of potato by reducing the applied irrigation water during the whole growing season by 30%; and three potato cultivars Agria, Almera and Sinora. For Agria and Almera, the experiments show that the full irrigation regime had the highest yield and water productivity as compared to IR1 and IR2 and cultivar Sinora was an exception. They recorded higher tuber dry weight percent under FI compared to IR1 and IR2 although the results varied among different cultivars.

Zhao *et al* (2014) made a comparison of three mulching areas and two ridge furrow shapes for two years (2009-10) to assess evapotranspiration, water use efficiency, and tuber yields in the semi arid north-west china. The experiment included five mulching area and ridge-furrow shape combinations: (1) full mulching on double ridges and furrow (DRFFM), (2) full mulch on both ridges and furrow (RFFM), (3) half mulching only ridges and furrow (RFHM), (4) no mulching on both ridge and furrow (RFNM), (5) traditional-flat planting and without mulching as the control (CK). Full mulching produced the highest tuber yields and water use efficiency with higher cost of mulching material and labour than the half or no mulching treatments. They reported that with increase in plant height LAI increased. They computed water use efficiency by using dry tuber weight (kg per ha) in the study.

Ahmadi *et al* (2014) studied partial root-zone drying (PRD) and deficit irrigations (DI) on the potato cultivar treatments Agria and Ramos. The whole growth period of both cultivars was divided into three stages based on the BBCH scale. There were five furrow irrigation treatments. The full irrigation treatment (FI) received 100% of potential evapotranspiration (ET); static deficit irrigation (SDI) received 75% of ET during the growth period; dynamic deficit irrigation (DDI) received 90% of ET in the first one-third of growth

period, 75% of ET in the second one-third of growth period, and 50% of ET in the last one-third of growth period; static partial root zone drying irrigation (SPRD) received 75% of ET during the growth period; dynamic partial root zone drying irrigation (DPRD) received 90% of ET in the first one-third of growth period, 75% of ET in the second one-third of growth period, and 50% of ET in the last one-third of growth period. Analysis showed that there were significant differences between irrigation strategies as DI did outperform PRD in tuber production. The SDI, DDI, SPRD, and DPRD irrigation treatments decreased the potato tuber yield by 4%, 7%, 56%, and 52% compared to FI, respectively. SPRD and DPRD decreased potato tuber yield by 54% and 48% compared to SDI and DDI, respectively. Water productivities (WP) were significant among irrigation strategies. Compared to FI, the SDI and DDI increased WP by 28% and 34%, respectively, but SPRD and DPRD decreased WP by 40% and 31%, respectively. In general, the DI strategy (SDI, DDI) was recommended in the study area due to the slight fresh tuber yield reduction (4%, 7%) and considerable increase (28%, 34%) in WP relative to FI. It was required to decrease the duration of wet/dry cycle under PRD strategy to guarantee efficient PRD and cope with extra water stress and hot weather in the region.

B. Effect of Irrigation scheduling on the quality of potato tubers:

Potato vines that remain wet for long periods create a microenvironment conducive to early blight (*Alternaria solani*), late blight (*Phytophthora infestans*), white mold (*Sclerotinia sclerotiorum*), and blackleg (*Rhizoctonia solani*) (Curwen, 1993). Internal brown spot was found to increase with over-irrigation during early tuber development (Hiller and Koller, 1984). Excessive soil moisture following planting can promote seed piece decay and an erratic emergence. Excessive irrigation can also erode hills, thus exposing shallow-set tubers to greening or sunscald and infection by early and late blight pathogens (Rowe and Secor, 1993). Adequate soil moisture helps reduce the attack of cutworms (*Spodoptera litura*) and mites (*Tetranychus* spp and *Tenuipalpidae* spp). Potato tuber moth (*Phthorimaea operculella*) and its larvae are repelled by soil moisture. Soil moisture also reduces formation of cracks in the soil, which allow the entry of potato tuber moth and its larvae (Grewal and Jaiswal, 1990).

Shock *et al* (1998) reported that under furrow and sprinkler systems, reductions in water applications for potato below full replacement of crop evapotranspiration, when silt loam soil is allowed to become drier than 60 kPa, result in yield reduction and loss of economic return. Total and U.S. No. 1 yield were reduced by deficit irrigation during all the three years. The proportion of misshapened tubers was directly related to soil water tension (SWT) irrigation criteria. Eldredge *et al* (1992) found that a single transient SWT stress drier than 50 kPa increased misshapen tubers. Pereira and Villa Nova (2002), while investigating

the effect of three SWT irrigation criteria on tuber yield and grade at Botucatu, SP, Brazil observed that potatoes irrigated at a 15 kPa to fully replace ET_c had higher yields and better quality than those when irrigated at 33 and 53 kPa. Curwen (1993) reviewed water management for potato and obtained best results on using the irrigation criterion of 65% available soil water (ASW). Measurements of soil water tension (SWT) that optimize potato yield and grade were determined for a number of locations, some of which were wetter than 65% ASW. Based on potato yield and grade responses to irrigation, ideal potato SWT irrigation criteria were 60 kPa and 30 kPa using furrow and drip irrigation, respectively, for silt loam in Oregon (Shock *et al* 1993, 2002). Short term deficit irrigation intensities resulted in dark stem-end fry colour and losses in tuber specific gravity (Shock *et al* 2003).

Wang *et al* (2011) conducted field experiments to study the effects of drip irrigation regimes on potato (*Solanum tuberosum* L.) when grown under plastic mulch in an arid area of North Western China in 2008, 2009 and 2010. The 2008 experiment consisted of a drip irrigation check without plastic mulch and four different drip irrigation frequency treatments with plastic mulch: once every day, once every 2 days, once every 4 days, and once every 8 days. In 2009 and 2010 the drip check treatment without mulch was irrigated at -25 kPa soil matric potential (SMP) during three potato development stages and four different SMP drip irrigation strategies were compared during the potato development stages (using plastic mulch): S1 (-25 kPa SMP during the three development stages), S2 (-25 kPa SMP during tuber initiation and bulking and -35 kPa SMP during maturation), S3 (-25 kPa SMP during tuber initiation and maturation and -35 kPa SMP during bulking), S4 (-35 kPa SMP during the three development stages). Plastic mulch negatively affected tuber yield, WUE, and tuber quality. In the presence of plastic mulch, tuber yield, specific gravity, and starch content seemed to be enhanced as the irrigation frequency increased, although the differences were not statistically significant. Under plastic mulch in 2010, S2 was the optimum drip irrigation regime because of the significantly higher yield than S3 and S4, the highest WUE and significantly firmer tubers than any of the other irrigation regimes tested.

Bisht *et al* (2012) conducted field experiment at Vegetable Research Centre of GB Pant University of Agriculture and Technology, Pantnagar. Seven treatments *i.e.*, 100% OPE (Open Pan Evaporation) daily (I₁), 80% OPE daily (I₂), 60% OPE daily (I₃), 100% OPE at alternate day (I₄), 80% OPE at alternate day (I₅) 60% OPE at alternate day (I₆) and control (I₇) *i.e.*, furrow irrigation given up to 5 cm depth at an interval of 15 days. The maximum number and yield of A (>75 g) and D (0-25 g) grade tubers was recorded in treatment I₄ (100 % OPE at alternate day) and I₆ (60% OPE at alternate day) respectively while, B (50-75 g) grade in I₂ (80% OPE daily) and C (25-50 g) grade under I₅ (80% OPE at alternate day). Dry matter content of tuber increased with increase in irrigation levels from 60, 80, 100% OPE

respectively, on daily as well as on alternate day basis in comparison to the control *i.e.*, furrow irrigation. The maximum dry matter content was recorded for I₄. Water use efficiency was found to be 0.70 t/ha mm in treatment I₆ compared to 0.15 t/ha mm in furrow irrigated crop. Water use efficiency was increased with decrease in irrigation levels applied either at alternate day or daily basis over the control (furrow irrigation). Water use efficiency was slightly higher with irrigation given at alternate day than daily basis. Maximum water was applied in furrow irrigated crop (I₇) (180.40 mm) followed by I₁ (88.50 mm) and I₄ (85.10 mm).

Cantore *et al* (2014) carried out a two-year field research (2009-2010) in Apulia region, southern Italy, on cv Spunta grown under three irrigation regimes: full irrigation (I₁₀₀), 50% of full irrigation (I₅₀) and rainfed (I₀). Plant water status, plant growth and, at harvesting, water use efficiency, yield and quality parameters were quantified. Water stress significantly affected yield response: as an average of the two years, a marketable yield decrement of 25.9 and 63.6% was observed in I₅₀ and rainfed compared with I₁₀₀ treatment, respectively. On the contrary, tuber dry matter and specific gravity increased moving from irrigated treatments to the rainfed one and varied also as a function of experimental year. The results confirmed that irrigation is required for early potato cultivation because rainfall is not sufficient to meet crop water needs. In addition, the study indicated that the irrigation regime reduced by 50% of crop water requirements was able to furnish satisfactory yield, with tuber quality characteristics similar or even better than those obtained under full irrigation.

Shahnazari *et al.* (2007) conducted experiments in potato (*Solanum tuberosum* L. cv. Folva) under open field conditions in 2004 and under a mobile rainout shelter in 2005. Two subsurface irrigation treatments were studied: full irrigation (F₁) receiving 100% of evaporative demands, 50.1 and 201 mm of irrigation water in the 2 years, to keep it close to field capacity; and PRD, which received 21.7 and 140 mm of irrigation in 2004 and 2005 respectively. Due to rain in 2004, the PRD treatment was imposed over a short period only during the late tuber filling and maturing stages. In 2005, the PRD treatment was imposed during the whole period of tuber filling and tuber maturation. The PRD treatment was shifted from one side to the other side of potato plants every 5–10 days. During the treatment period, plants were harvested five times, and no significant difference was found between the treatments in leaf area index, top dry mass and tuber yield. At final harvest, tuber yield of important marketable class (C₂: tubers between 40 and 50 mm diameter) was significantly higher (20%) in the PRD than in the F₁ treatment. Compared with F₁, the PRD treatment saved 30% of irrigation water while maintaining tuber yield, leading to a 61% increase of irrigation water use efficiency.

Qin *et al.* (2014) investigated six treatments: (1) a flat plot without mulch (CK); (2) alternating mulched with plastic film and bare plots with no ridges (MNR); (3) completely mulched alternating wide and narrow ridges with furrow planting (CF); (4) completely mulched alternating wide and narrow ridges with ridge planting (CR); (5) alternating mulched ridges and bare plots with no ridges and with furrow planting (HF); (6) alternating mulched ridges and bare plots with no ridges and with ridge planting (HR). Ridge-furrow plastic mulching planting pattern systems greatly improved tuber yield and WUE of potato in comparison to CK. CF and CR treatments resulted in higher dry matter and relative growth rate than other treatments, and had higher output efficiency of dry matter from aboveground to tuber. Potato in CR showed the highest tuber yield, output value, net revenue and WUE, produced tubers with good size, low percentages of green and blemished tubers, and high protein content. In conclusion, CR is the best planting pattern for rain-fed potato.

Carli *et al* (2014) while evaluating the effects of different irrigation regimes in Uzbekistan reported that the reduction of water supply after tuberization had a limited effect on yield but it increased starch and dry matter content.

C. Irrigation scheduling to potato under different crop establishment methods:

Mundy *et al* (1999) compared a wide bed production system (3 rows of potatoes planted on a 1.9 m flat-topped raised bed) to a conventional-ridged system (1 row of potatoes in sharply sloped ridges on 96 cm centers) in 1996 and 1997 on a Norfolk sandy loam soil and a Portsmouth fine sandy loam soil in eastern North Carolina. Soil moisture, Potato plant stands, leaf area index at approximately 9 WAP, yield, and quality were measured. Wide beds were more moist than conventional ridges early in the season. The row on the west side of an individual wide bed was most similar to conventional ridges in daily soil temperature fluctuations between minimum and maximum temperatures. Total yield and yield of grade A potatoes were not significantly different between wide beds and conventional ridges at either site. At one site, yield of grade B potatoes was significantly less in the wide bed; among the three rows in the wide bed, the eastern row had significantly lower yield of grade B potatoes. Conventional ridges had a higher percent of green grade A potatoes than the wide beds in one of three trials. The authors suggested that changing production systems would be unadvisable for most growers because wide beds do not increase yield enough to justify spending the money for more seed and to change equipment.

Panigrahi *et al* (2001) conducted field experiments to study the effects of plant-furrow treatments and levels of irrigation on potato water use, yield and water-use-efficiency in a sandy loam soil of Orissa. The two plant furrow treatments were F₁- furrows with single row of planting in each ridge with 45 cm distance between adjacent ridges, and F₂- furrows with double rows of planting spaced 30 cm apart in each ridge with 60 cm distance between

adjacent ridges. The two levels of irrigation were I_1 - 0.9 IW/CPE and I_2 - 1.2 IW/CPE, where IW is irrigation water of 5 cm. the treatment F_2 produced highest tuber yield in all years with average value of 10.6 t ha^{-1} and 12.8 t ha^{-1} at I_1 and I_2 levels of irrigations, respectively. It was observed that six irrigations with total of 25 cm and seven irrigations with total of 30 cm irrigation water were required for both F_1 and F_2 at I_1 and I_2 , respectively. The treatment F_2 resulted in a significantly higher number of branches and tubers per plant, foliage coverage and water use efficiency for both irrigation levels than treatment F_1 .

Pereira *et al* (2005) studied the effect of irrigation systems and cultural practices on potato performance. Six irrigation and bed configuration treatments were chosen for irrigation system, bed design, irrigation criteria, and straw mulch to reduce soil temperature which were; T_1 – Sprinkler irrigation, potato seeds planted in ordinary beds (rows bedded into 36-inch hills), with irrigation starting whenever the SWT was equal to 60 kPa; T_2 – Drip irrigation, potato seeds planted in flat beds, with irrigation criterion based on a SWT of 30 kPa, with the expectation that the total irrigation amounts would correspond to about 70 percent of crop evapotranspiration (ET_c); T_3 – Drip irrigation, potato seeds planted in flat beds with irrigation criterion based on a SWT of 30 kPa, with daily irrigation matching ET_c ; T_4 – Furrow irrigation, seeds planted in ordinary beds, with irrigation starting when SWT reached a threshold of 60 kPa; T_5 – Sprinkler irrigation, seeds planted flat in 36-inch rows, irrigation criterion of 60 kPa, and with irrigation amounts to match ET_c ; T_6 – Sprinkler irrigation, seeds planted flat in 36-inch rows, with irrigation starting at a SWT of 60 kPa, soil receiving 2,000 lb/acre of straw mulch at tuber initiation (on June 6), and irrigation amounts to match ET_c . The SWT was measured by granular matrix sensors at six locations in every plot at 8-inch depth below the surface in the plant row. Irrigation episodes were scheduled to avoid SWT in the root zone exceeding the threshold of 30 kPa under drip system for T_2 and T_3 , and of 60 kPa under furrow- and sprinkler-irrigation systems for treatments T_1 , T_4 , T_5 , and T_6 . The highest marketable tuber yield and US grade No. 2 tubers were obtained in the T_2 treatment, while higher marketable tuber yield at par with T_2 and US grade No.1 tubers were obtained in the T_3 .

Harms *et al* (2010) studied agronomic practices for potato production in the irrigated areas of southern Alberta involving a hill/furrow configuration that was adopted from elsewhere, and designed to shed rainfall away from the hill and into the furrow. A three-year project was started in 2006 to quantify the potential irrigation water savings of altered hill shapes for potato production. The three treatments (standard hill, flat-topped hill, and double-planted wide-bed) were arranged in a randomized strip plot design replicated four times. Soil water in each treatment was made available between 60 and 90 per cent. A fourth treatment, triple-planted wide bed, was added to the project in 2008. The irrigation requirements to

maintain the treatments were 487, 442, and 449mm for the standard hill, flat-topped hill, and double-planted bed, respectively, in 2006 and 442, 408 and 411mm for the same treatments in 2007. This translated into approximately 10% less irrigation water required for the flat-topped hill shape compared to the standard hill shape. The flat-topped hill shape required 5.0% more irrigation than the standard hill in 2008, but the double and triple-planted wide beds required 8.0 and 9.9%, respectively, less irrigation water than the standard. Water use efficiency was greater in all years for the altered bed shapes compared to the standard hill geometry. Total yield was greater in 2006 for both the flat-topped hill (72.3 Mg ha⁻¹) and wide-bed hill (69.2 Mg ha⁻¹) compared to the standard hill (61.4 Mg ha⁻¹). Significantly greater marketable yield was realized from the flat-topped hill treatment in 2006. This treatment also had a significantly greater number of marketable size tubers. In 2007, the standard and flat-topped treatments had a significantly greater number and yield of tubers in the 113–170 g size category. Significant differences in total yield were found in 2008. The triple-planted wide bed had significantly greater yield in the smaller size categories compared to the standard treatment and significantly greater total tuber numbers than the other treatments, but the increase was in the smaller size categories, less than 170 g. There were no significant differences among the treatments in yield or total number of tubers in the size categories greater than 171 g in 2008.

Singh *et al* (2010) conducted a field studies were during rabi season of 2003-2007 on light textured (Typic-Ustocrept) soils at CPRIC, Modipuram, Meerut (UP) to investigate the effect of raised bed planting patterns and drip layout systems on yield and economics of potato. Results revealed that the total yield (363 q/ha) and tuber numbers (709 thous/ha) were significantly higher in triple row planting with 1,25,000 plant density/ha along with single drip placed at 120 cm distance on each bed in comparison to furrow irrigation method (283 q potatoes and 586 thous. tubers/ha). Similarly, the medium/seed size tuber yield (230 q/ha) was also maximum in triple row bed planting under drip irrigation. However, the yield of large grade tubers (148 q/ha) and average tuber weight (55.8 g) were observed maximum under single row planting with 83,333 plant density/ha when drip was placed at 60 cm distance on each ridge. Plant height and number of leaves/plant were significantly higher under drip irrigated crop, but, the number of stems/plant did not differ significantly. The benefit: cost ratio in triple row planting with 1,25,000 plants/ha was comparably lower (1.61) than double row planting due to higher seed rate used which increased cultivation cost, but produced significantly higher seed size tuber yield and numbers under drip irrigation. Water use efficiency (157 kg potatoes/ha-mm) was higher under triple row planting with 1,25,000 plants/ha along with the single drip placed at 120 cm spacing on each bed in comparison to other planting pattern and drip layout systems.

Qasim *et al* (2013) carried out an experiment at Himalayan Agricultural Research Station (HARS), Kaghan, Pakistan during the summer season of 2005. The results showed that maximum tuber growth (88.7%), average number of tubers per plant (10.1) and yield per hectare (12.4 t/ha) were significantly different and higher when potatoes were planted on wide bed and covered with soil from one side. Tallest plants (53.4 cm) were observed when potatoes were sown on the ridges. Maximum number of green potatoes (12.5) and injured potatoes (5.3%) were observed when the tubers were planted following local farmers' method.

Singh and Sood (2013) conducted field studies during two consecutive years (2008-09 and 2009-10) on light textured (Typic-Ustocrept) soils at CPRI Campus, Modipuram, Meerut, to sustain potato productivity through raised bed planting techniques under furrow and sprinkler methods of irrigation. The treatments comprised of: (i) traditional planting under furrow irrigation, (ii) paired row raised bed planting at 90 cm (1,11,111 plants/ha at 20 cm inter & 20 cm intra row spacing on each bed), the bed: furrow size; 60 cm x30 cm under furrow irrigation, (iii) triple row raised bed planting at 120 cm (1,25,000 plants/ha at 20 cm inter and 20 cm intra row spacing on each bed), bed: furrow size; 90 cm x30 cm under furrow irrigation. The total yield and net yield was higher under traditional planting on the ridges under furrow irrigation as compared to raised bed planting. Similarly, average tuber weight and tuber yield for large tubers (< 75g) was higher under traditional planting as compared to raised bed planting. Although the total number of tubers was higher under raised bed planted plots compared to traditional planting plots but net number of tubers seemed to be similar for them.

Ati *et al* (2012) conducted a study to determine the effect of different irrigation methods and potassium fertilizers on potato yield in the Abu-Graib-Baghdad, Iraq Region, during season 2011–2012. Potato was grown under furrow and drip irrigation methods. Furrow and drip irrigation methods had no significant effect on tuber yield under the experiential conditions. IWUE of drip-irrigated treatments were higher and differed from furrow-irrigated treatments in the growth season ($P < 0.05$). The drip-irrigated treatments produced higher WUE in comparison to furrow-irrigated in all treatments in the growth season ($P < 0.05$). The water use efficiency of all the treatment ranges from 5.129 to 10.257 kg m⁻³ while the irrigation water uses efficiency ranges from 5.868 to 12.216 kg m⁻³. Drip irrigation method yielded higher values of IWUE and WUE, since drip irrigation consumed less water than furrow irrigation.

The reviewed literature showed that there were few studies available which defined most suitable soil matric potential at a depth which is suitable for better root growth and

nutrient exploitation. There was thus need to carry out detailed studies for working out the most optimum soil matric potential and its depth of measurement.

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CHAPTER – III

PUBLISHED/ACCEPTED/SUBMITTED RESEARCH ARTICLES

S. No.	Publications	Name of the Journal	NAAS Rating	Status
1.	Effect of irrigation scheduling on tuber yield of potato under different crop establishment methods	International Journal of Food Agriculture and Veterinary Sciences (ISSN: 2277-209X)	(ICV: 5.87)	Accepted
2.	Effect of soil matric potential based irrigation scheduling on water use efficiency of potato	International Journal of Food Agriculture and Veterinary Sciences (ISSN: 2277-209X)	(ICV: 5.87)	Accepted
3.	Scheduling irrigation to potato based on soil matric potential criterion under north-western Indian plains	Agricultural Water Management (ISSN:0378-3774)	8.2	Submitted
4.	Irrigation scheduling under different crop establishment methods in north-western plains of India	Agricultural Water Management (ISSN:0378-3774)	8.2	Submitted
5.	Effect of soil matric potential based irrigation scheduling on yield and quality of potato tubers in the north-western Indian plains	Potato Journal (ISSN:0970-8235)	4.88	Submitted

EFFECT OF IRRIGATION SCHEDULING ON TUBER YIELD OF POTATO UNDER DIFFERENT CROP ESTABLISHMENT METHODS

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ABSTRACT: A field investigation was conducted to find out the optimal irrigation schedule under different crop establishment methods in sandy loam soil in North-Western plains of India during 2012-13 and 2013-14. The experiment comprised of climatic and soil matric potential based irrigation treatments: I₁: IW/CPE: 1.00, I₂: IW/CPE: 1.25, I₃: IW/CPE: 1.50, I₄: S₃₅D₂₀ and I₅: control (farmers practice). These treatments were compared under furrow-ridge (M₁) and furrow-bed planting (M₂) system. The experiment was conducted in split plot design and it was replicated thrice. The ridge-furrow planting method proved better than bed-furrow system in terms of marketable tuber yield, large and medium sized tuber yield and average tuber weight. Treatment I₄ recorded more than twice increase in irrigation water use efficiency as compared to control as well as enhanced the graded and marketable tuber yield as compared to all other treatments under ridge-furrow planting system. The results suggest that scheduling irrigation based on soil matric potential at -35 kPa measured at soil depth of 20 cm under ridge-furrow irrigation system is a better option under the North-Western plains of India.

INTRODUCTION: Potato is a major food crop in the world with an estimated production of 368.1 million tonnes (Anonymous, 2013). India is the second largest producer of potatoes after China with a production of 45.3 million tonnes from an area of 1.99 million ha (CPRI, 2013). In the Indian state of Punjab (North-Western India) the area and production under potato has witnessed five and eight times increase, respectively in the last fifty years with present production of about 2 million tonnes (CPRI, 2013).

The ridge-furrow planting system which use furrow irrigation method is mostly adopted for potato planting in the North Indian plains. In the prevailing method of furrow irrigation, most of the irrigation water infiltrate down the root zone area without its proper absorption by the roots. Bed planting has been found beneficial for improving yield and water use efficiency in potato (Fisher, 1995; Sidhu et al., 2005; Harms and Korschuh 2010; Singh et al., 2010; Qasim et al., 2013). Varying geometries of ridge planting has been studied by various scientists for improving the tuber yield and quality (Singh et al., 2010; Bombik et al., 2013; Singh and Sood, 2013; Vitos, 2013).

Keeping in view the increasing demand of water and area under potato crop especially in the Indo-Gangetic plains of India, there is a need for evaluating accurate irrigation schedule to improve irrigation water use and energy use efficiency (Gulati and Singh, 2011). Scheduling of irrigation in any crop depends upon soil type, crop variety, methods of planting as well as location. In India, pan evaporation based irrigation schedule has been recommended for potato cultivation by Directorate of All India coordinated project for research on water management. But more recently, Medici et al., (2014) has suggested

that soil water tension is a good technique for scheduling irrigation to the different crops which needs further studies. This technique requires simple instrument like tensiometer for irrigation scheduling. A preliminary study conducted by the authors (unpublished) has established scheduling of irrigation at SWT of 35 kPa for higher yield and better tuber quality under furrow-ridge irrigation system for sandy-loam soils in the North-Western Indian plains. Further study was planned to compare the SMP based irrigation schedule with the pan evaporation based irrigation scheduling under the two crop establishment methods of ridge-furrow and bed-furrow planting system.

Considering all these factors, this study was undertaken with the objective to find out the best irrigation schedule for maximizing tuber yield, and quality under different crop establishment methods in the North-Western plains of India.

MATERIALS AND METHODS

Site, climate and soil

The investigation was undertaken on a typical Ustipsamment soil at Vegetable Research Farm, Department of Vegetable Science, Punjab Agricultural University, Ludhiana (Punjab) India for two potato growing seasons (October to January) in 2012-13 and 2013-14. The climate of Ludhiana is subtropical, semi-arid with an annual rainfall of 755 mm. Major part of the annual rainfall is received during June to September known as monsoon. Soil type was sandy loam with composition of 71 % sand, 19% silt and 10% clay. The experimental site in 2012 has: pH 7.9, electrical conductivity: 0.24 dS m⁻¹, organic C 3.5 g kg⁻¹, 0.5 M NaHCO₃ extractable P (Olsen et al., 1954) 8.0 mg kg⁻¹ and K (Pratt, 1965) 172.5 mg kg⁻¹, and in the year 2013 these values were pH: 7.8, EC: 0.21 dS m⁻¹, OC: 3.5 g kg⁻¹, extractable P: 7.75 mg kg⁻¹ and K: 171.0 mg kg⁻¹. The details of other physical characteristics observed before planting the crop at experimental sites are shown in table 1.

Table 1: Physical characteristics of soil during the year 2012 and 2013

Soil depth (cm)	Bulk density (g cm ⁻³)		Saturated conductivity (cm hr ⁻¹)		Unsaturated conductivity (cm hr ⁻¹)				Infiltration rate (cm hr ⁻¹)	
					Suction I (2cm)		Suction II (4cm)			
Year	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013
0-15	1.36	1.33	310.0	312.0	104.0	106.0	33.0	32.0	7.05	6.85
15-30	1.50	1.48	140.0	145.0	28.0	30.0	10.0	12.0		
30-45	1.63	1.64	144.0	140.0	14.0	13.0	13.0	15.0		
45-60	1.69	1.70	115.0	120.0	23.0	25.0	22.5	24.0		

Field Experiment Design

The experiments were conducted in split plot design with four replications. There were two main plots comprising ridge-furrow (M_1) and bed-furrow (M_2) planting systems. The treatments under sub-plots consisted of five irrigation levels: I_1 ; IWCPE (Irrigation water to cumulative pan evaporation) ratio 1.0, I_2 ; IWCPE ratio 1.25, I_3 ; IWCPE ratio 1.5, I_4 ; $S_{35}D_{20}$ (Maintaining suction 'S' of 35 kPa by installing tensiometer at soil depth 'D' of 20 cm) and I_5 ; control (farmers practice in the region). Each ridge was spaced at 60 cm from another ridge and it was followed by a furrow in ridge-furrow planting system. Beds with 85 cm top and 120 cm bottom width were prepared each followed by a furrow under bed-furrow planting method. Ridge-furrow and bed-furrow plots were prepared using semi-automatic potato planter and bed planter respectively, and planting was done manually. Plots measuring 10.0 m $\times$ 5.2 m (gross plot size) comprising eight ridges and four beds under bed-furrow each followed by a furrow under bed planting method of planting were prepared. Two rows of potatoes were planted on each bed. Two metre wide border was kept between two adjacent plots as well from irrigation channel to prevent unwanted water seepage. Disease free tubers of Kufri Pukhraj were planted 20 cm apart on top of the ridges. A performa was prepared and filled after polling and personal interviews with the farmers for collecting information regarding crop and irrigation management practices followed by them before finalizing irrigation scheduling for control treatment.

Crop management

Pre-sprouted seed tubers weighing approximately 45g each were planted at the spacing of 60 $\times$ 20 cm under ridge-furrow and 45 $\times$ 27 cm on the bed (equivalent to a maintaining equal plant density of 8.33 plants m^{-2}) on 18th October 2012 and 15th October 2013. Planting was done in the dry soil for control plot and in pre-irrigated soil for all other treatments during both the years. All plants emerged 19 and 21 days after planting during the first and second years respectively. Standard crop management practices as per the recommendations of PAU, Ludhiana were followed for raising successful crop. Potato vines were dehaulmed 90 days after planting and tubers were lifted 15 days after dehaulming for hardening of tubers. The tubers were harvested on 31 January 2013 and 28 January 2014. The yield parameters were recorded at the time of harvest.

Irrigation treatments:

Good quality irrigation water (EC: 0.5 dS m^{-1}) was given to facilitate the rooting and establishment of the crop for its complete emergence and for this purpose all plots received 5 cm of pre-plant irrigation water except control plots. The control plots received 11 and 9 cm

and other plots received 5 and 4 cm post-plant irrigation water under ridge-furrow and bed-furrow planting system, respectively for proper establishment of the crop (Table 2). After these common irrigations, rest irrigations were applied as per the treatment schedule. However, the control treatment received first irrigation 10 days after complete emergence and remaining irrigations at an interval of 12 days. Additional irrigation was given to control plots during the days when there were chances of frost occurrence. Only rainfall exceeding 5 mm within 25 hr was considered effective and included in the calculations for total water use.

Dial vacuum gauge tensiometers were installed at 20 cm depth on the ridge (from the top surface of the ridge) between two plants in the middle potato row of each I_4 plot. Monitoring of tensiometers was started regularly for SMP reading after the complete emergence of the crop. The readings were observed daily between 8.00 a.m. and 9.30 a.m. and irrigation was applied thereafter as per requirement of the treatment. The irrigation schedule under I_1 to I_3 treatment plots was followed as per the targeted IW:CPE ratios.

Data Collection:

At tuber harvest, 50 plants from each plot were harvested by randomly selecting middle three rows of potatoes; the tubers were picked manually, counted, graded based on the tuber weight and weighed to determine average tuber weight, graded and marketable tuber yield. The four grades were selected based on tuber weight i.e. large (>100 g), medium (≥ 75 g), small (≥ 50 g) and smaller (≥ 50 g).

The irrigation water use efficiency (WUE_i) was computed based on the marketable tuber yield by using the following formula
$$WUE_i = \frac{\text{Marketable tuber yield (Kg/ha)}}{\text{Total irrigation water (mm)}}$$

where, Total irrigation water = water given to various treatments through irrigation.

Meteorological data

Meteorological data were recorded at meteorological station situated nearby the experimental site. Weekly average temperature, relative humidity, sunshine and total rainfall and evaporation during the potato growing period from October, 15 to January, 31 in 2012-13 and 2013-14 seasons, respectively were recorded (Fig. 1 & Fig. 2).

Data Analysis

Two years data were subjected to analysis of variance (ANOVA) (Gomez and Gomez, 2010) based on PROC GLM (SAS software 9.1). Duncan's multiple range tests at $p=0.05$ was applied to compare the means of different treatments.

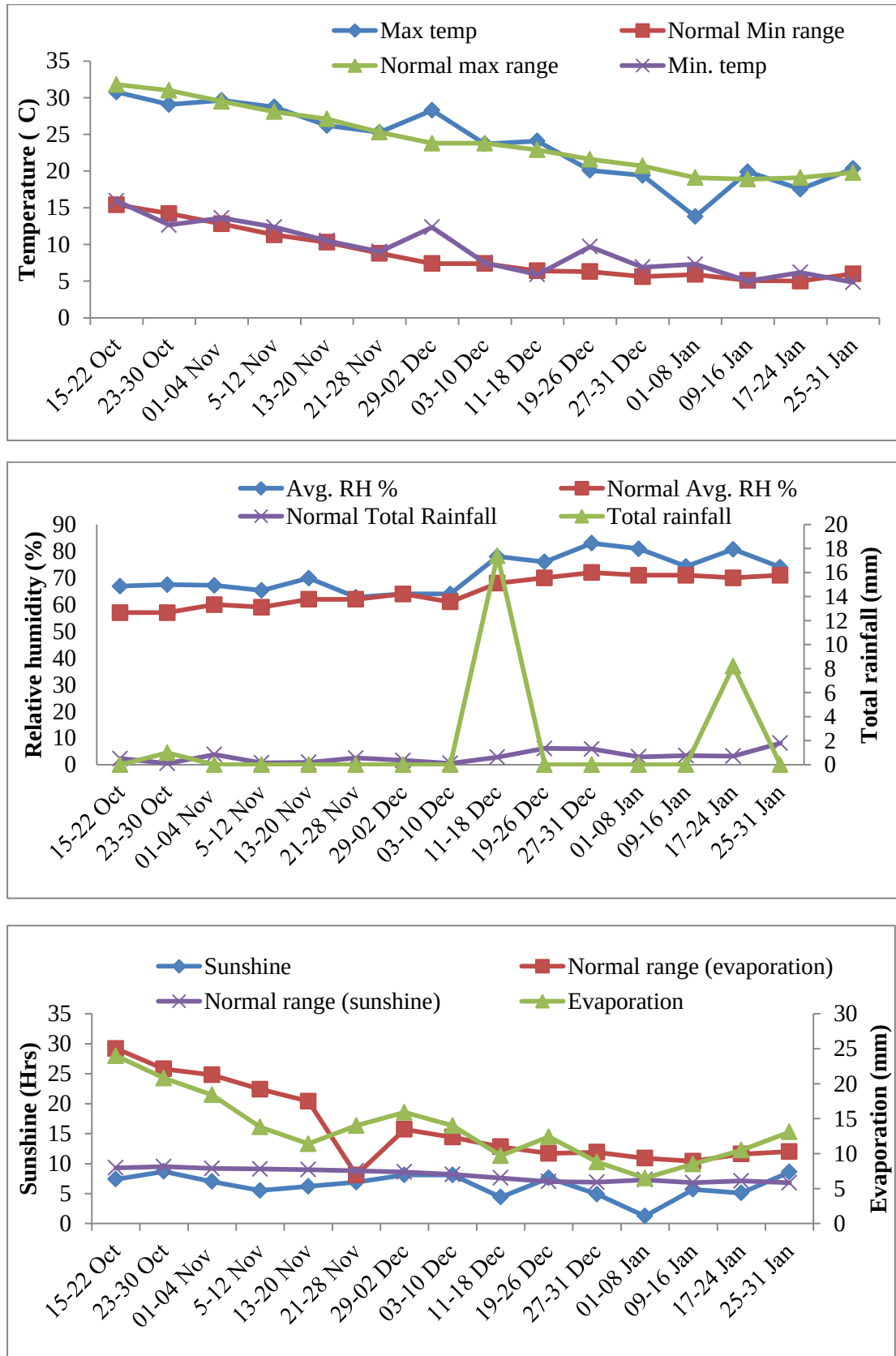


Fig. 1. Maximum and Minimum temperature (°C) (a), average humidity percent and total rainfall (mm) (b), sunshine (Hrs) and Evaporation (mm) (c) during 2012-2013.

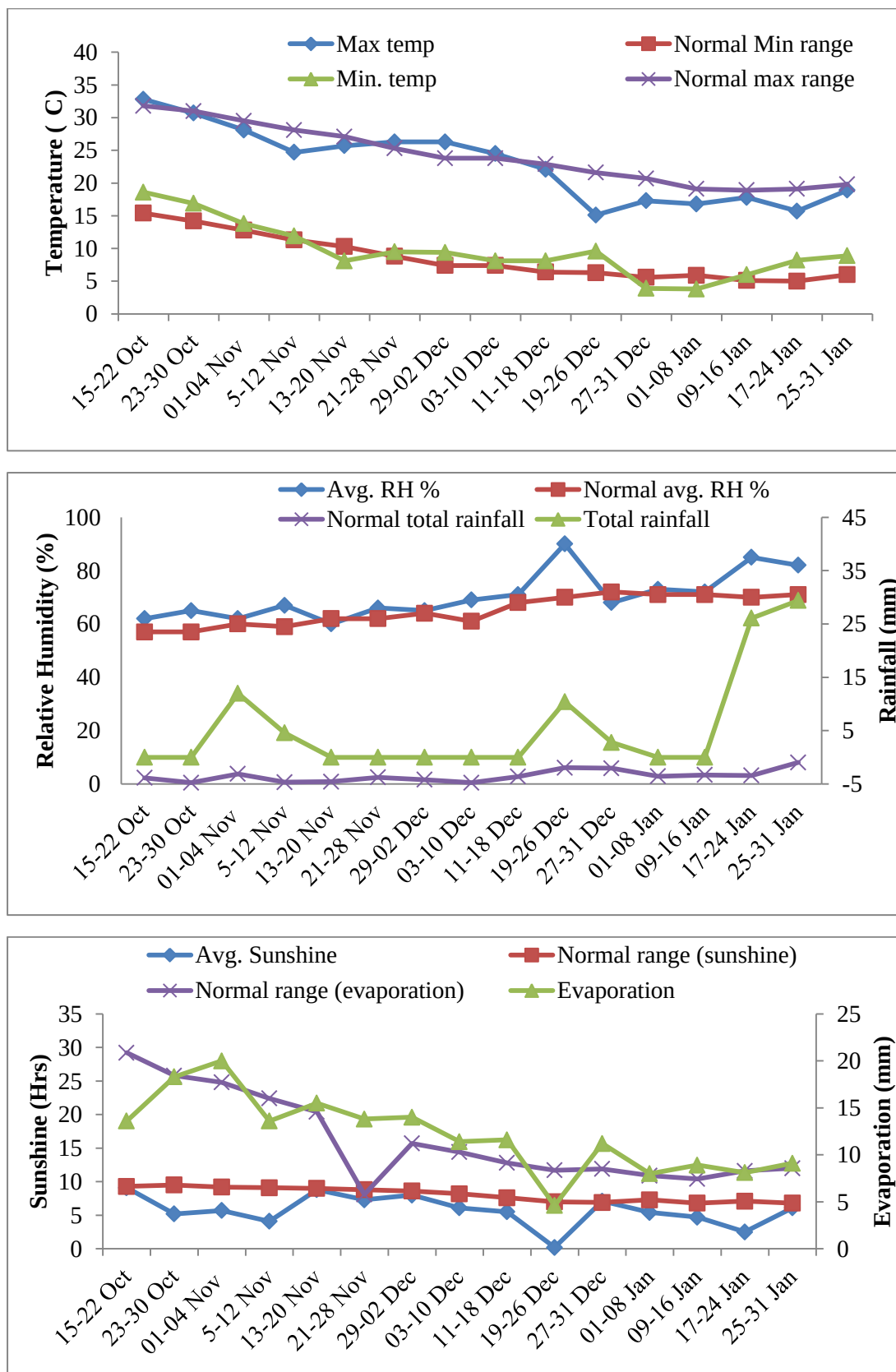


Fig. 2. Maximum and Minimum temperature (°C) (a), average humidity percent and total rainfall (mm) (b), sunshine (Hrs) and Evaporation (mm) (c) during 2013-2014.

Total Rainfall

Total rainfall was not uniformly distributed and was lower than the normal range during 2012-13 potato growing season [Fig. 1 (a to c)]. There were two events of rainfall above 5 mm measuring 25.6 mm of water in the IIIrd week of December (17.2 mm) and IIIrd week of January (8.2 mm). But the rainfall that occurred in IIIrd week of January was not considered for further calculations as this event occurred when the crop had approached maturity.

During the 2013-14 potato growing period, there were three effective events of rainfall above 5 mm measuring in total 48.5 mm water [Fig. 2 (a to c)]. One event of rainfall (12 mm) occurred in the Ist week of November and second event (10.4 mm) occurred in last week of December. The rainfall that occurred in the IIInd and IIIrd week of January (26.1 mm) were not of much use as crop was approaching near maturity and the same was not considered for doing further calculations.

RESULTS AND DISCUSSION

Irrigation water and irrigation water use efficiency

It was observed that approximately 10 % lower water volume was utilized under bed planting than that of ridge planting during both the years (Table 2). Highest irrigation water was used under the control during both the years and methods. Total water volume utilized varied from 2524 to 5124 m³ ha⁻¹ during first year and 2154 to 5524 m³ ha⁻¹ during the second year under ridge-furrow planting method. The corresponding values under bed-furrow method of planting were 2274 to 4224 and 2354 to 4274 m³ ha⁻¹ during first and second year, respectively. Irrigation water use efficiency (WUEi) did not vary with the methods of planting. Treatment I₄ recorded significantly higher WUEi among all the irrigation treatments during both the years as well as under both the planting methods. Treatment, I₄ recorded 138% higher WUEi than that of control as 52% water volume was saved during the first year and the corresponding values during the second year were 167% and 60% under ridge-furrow method of planting (M₁). The corresponding values for the same treatment in the second year under bed-furrow method of planting (M₂) were 123% & 48% and 129% & 53%. Sidhu *et al.* (2005) also recorded higher water use efficiency by maintaining soil matric suction of 20±2 kPa under different planting methods. The control treatment recorded lowest water use efficiency during both the years of planting because maximum irrigation water was received by these treatments.

Table 2: Irrigation water application and water use efficiency during the year 2012 and 2013

Method of planting	M ₁ (Ridge-furrow method)												M ₂ (Bed-furrow method)											
Irrigation treatments	I ₁		I ₂		I ₃		I ₄		I ₅		Mean		I ₁		I ₂		I ₃		I ₄		I ₅		Mean	
Year	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013
Irrigation application (mm)	235	193	235	238	280	286	235	236	495	590	296	309	210	213	250	254	250	254	210	213	405	450	265	277
Total water application (m ³ ha ⁻¹)	2524	2154	2524	2604	2974	3084	2524	2589	5124	5524	3132	3311	2274	2354	2674	2764	2674	2764	2274	2354	4224	4274	2822	2992
WUE _i (kg ha ⁻¹ mm ⁻¹)	60.8b	78.1b	68.7b	65.7c	68.0b	62.2c	92.5a	87.2a	38.8c	32.6d	65.8a	65.0a	64.5bc	64.2b	58.1c	56.3b	67.7b	62.3b	94.4a	85.3a	42.4d	37.3c	65.4a	61.1a

Column means followed by the same letter are not significantly different at p<0.05

Table 3: Tuber yield and quality characters as affected by methods of planting and irrigation during the year 2012 and 2013

Method of planting	M ₁ (Ridge-furrow method)												M ₂ (Bed-furrow method)											
Irrigation treatments	I ₁		I ₂		I ₃		I ₄		I ₅		Mean		I ₁		I ₂		I ₃		I ₄		I ₅		Mean	
Year	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013
Avg. Tr wt (g)	30.9b	31.9b	37.2b	36.3b	47.1a	47.3a	52.9a	51.6a	48.9a	48.6a	43.4a	43.1a	32.0c	30.6c	34.2c	34.1bc	43.4b	40.9ab	49.5a	43.8a	46.4ab	44.4a	41.1a	38.8b
Mkt. Tr yield (q/ha)	143.0c	150.7d	161.4c	156.4cd	190.4b	177.8bc	217.3a	206.8a	192.2b	183.6ab	180.8a	175.1a	135.4c	136.8b	145.4c	142.9b	169.3b	158.2ab	198.2a	181.8a	171.8b	167.8a	164.0b	157.5b
Large Tr yield (q/ha)	15.1b	14.3c	18.3b	17.1c	28.2a	23.8b	31.7a	31.0a	28.8a	25.7ab	24.4a	22.3a	11.3b	9.3c	12.7b	11.4bc	17.3b	15.2abc	24.8a	20.3a	17.6b	17.1ab	16.7b	14.6b
Med. Tr yield (q/ha)	24.7d	27.2c	32.42c	29.9c	44.5b	43.6b	55.0a	52.3a	42.8b	40.4b	39.9a	38.6a	18.3c	16.3b	20.8c	19.4b	30.1b	29.7a	39.1a	33.7a	32.2b	29.9a	28.1b	25.8b
Small Tr yield (q/ha)	38.6c	41.1d	44.7c	43.8cd	54.5b	49.2bc	62.5a	59.2a	56.1b	53.7ab	51.3a	49.4a	40.5c	41.1c	45.0c	43.7bc	56.5b	48.3b	63.6a	58.8a	56.5b	55.0a	52.4a	49.4a
Smaller Tr yield (q/ha)	64.5a	68.2a	65.9a	65.7ab	63.3a	61.2b	68.2a	64.4ab	64.5a	63.8ab	66.7a	64.7b	65.2b	70.1a	67.0ab	65.8a	65.4b	65.1a	70.6a	69.1a	65.5b	65.8a	65.3a	67.7a

Column means followed by the same letter are not significantly different at $p < 0.05$ * Avg. Tr wt= Average tuber weight, Mkt. Tr yield= Marketable tuber yield, Med. Tr yield= Medium sized tuber yield

Average tuber weight and marketable tuber yield

The analysis of data revealed that average tuber weight was significantly higher under ridge-furrow (M_1) in comparison to the bed-furrow planting method during the second year. It was significantly higher for I_3 , I_4 and I_5 under M_1 and I_4 treatment under M_2 method of planting during both the years and for I_5 treatment under M_2 during the second year. The treatments I_3 , I_4 and I_5 under M_1 method of planting have received higher amount of irrigation water which may probably have resulted in better moisture content in the root zone for better growth and development of tubers. Similarly, the treatment I_4 under bed-furrow method of planting may have received optimum soil moisture for the better tuber development. Singh and Sood (2013) also obtained higher average tuber weight in the traditional ridge-furrow planting as compared to the raised bed planting. The method of planting significantly affected the marketable tuber yield which was significantly higher under M_1 i.e. ridge-furrow planting method as compared to M_2 , method of planting. The lower marketable tuber yield under bed planted crop may be due to moisture stress in the vicinity of the root zone area as the plantation was near the centre of beds. Sidhu et al., (2005) also reported lower tuber yield under 90 cm wide beds as compared to the 60 cm wide beds. In our study also bed width on the top was 85 cm. However, our finding is in contrary to the results of Qasim *et al.* (2013), who had reported higher tuber yield under wide beds as compared to the ridge planted crop. Among the various irrigation treatments, marketable tuber yield was significantly higher for I_4 treatment under both the planting methods and years and this treatment was statistically at par with I_5 treatment during the second year. Treatment I_4 recorded 13.1% and 12.6% higher tuber yield than that of control under ridge-furrow planting system during first and second years, respectively and the corresponding values under bed-furrow planting method were 15.4% and 8.3%. The treatment I_5 under M_2 method of planting also recorded significantly higher marketable tuber yield which was statistically at par with I_3 treatment during the second year. The recording of higher marketable tuber yield under ridge-furrow planting method evidenced the advantage of this method over the bed-furrow planting. The irrigation treatments which registered higher marketable tuber yield may probably have received the proper amount of irrigation water for keeping optimum soil moisture in the root zone for higher production of healthy tubers.

Graded tuber yield

Graded tuber yield was significantly affected by method of planting except for small size tubers during both the years and smaller size tubers for first year. Among the two methods, ridge-furrow planting method (M_1) recorded significantly higher tuber yield for large and medium sized tubers during both the years. However, M_2 showed significantly higher tuber yield for smaller sized tubers during the second year. Among different irrigation treatments, I_4 treatment during both the years and I_3 and I_5 during the first year under M_1 method of planting

recorded significantly higher large sized tuber yield. Under M_2 method of planting, I_4 recorded significantly higher large sized tuber yield and treatments, I_3 and I_5 for second year were statistically at par with I_4 . Treatment, I_4 recorded significantly higher medium and small sized tuber yield both under M_1 and M_2 methods during two years. Under M_2 method of planting, I_5 treatment recorded significantly higher medium and small sized tuber yield during the second year. Medium sized tubers yield for I_3 treatment during second year under M_2 was also significantly higher. It is evident that the I_3 , I_4 and I_5 treatments recorded higher large and medium sized tuber yield which indicates that under these treatment, tubers gathered higher biomass. It may probably because of proper moisture in the root zone which may have resulted in better growth and development of tubers. Similarly, Singh and Sood (2013) and Singh et al., (2010) also recorded higher tuber yield of large sized ($>75g$) tubers under conventional ridge-furrow system as compared to raised bed planting. In our study, medium size tubers were $>75g$, thus our results were similar to earlier findings. All the irrigation treatments under M_1 recorded statistically at par values of smaller sized tuber yield during both the years. Similarly smaller sized tuber yield was statistically at par for all the irrigation treatments under M_2 method of planting during the first year.

The advantage of ridge-furrow planting method over bed-furrow planting method in terms of marketable tuber yield, large and medium sized tuber yield and water use efficiency supported the relevance of ridge-furrow planting system over that of bed-furrow planting method. Singh and Sood (2013) also reported that raised bed planting of double and triple row planting of potato is non advantageous as compared to conventional ridge planting under furrow irrigation method.

In conclusion, higher graded and marketable tuber yield and average tuber weight under ridge-furrow planting method was recorded as compared to bed-furrow planting method. About three times higher irrigation water use efficiency was recorded by I_4 treatment as compared to the control (farmers practice) along with saving of 48 to 60% irrigation water. This suggests that irrigation scheduling based on soil matric potential by following ridge-furrow irrigation system is a better criterion in our conditions than that of climatic based irrigation scheduling. Thus, irrigation scheduling by fixing -35 kPa SMP at soil depth of 20 cm from top of the ridge is the best treatment under our conditions.

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EFFECT OF SOIL MATRIC POTENTIAL BASED IRRIGATION SCHEDULING ON WATER USE EFFICIENCY OF POTATO

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ABSTRACT: A field investigation was conducted with the objective to determine effect of soil matric potential based irrigation scheduling on water use efficiency under furrow-ridge irrigation system in sandy loam soil during 2011-12 and 2012-13. Three levels of soil matric suction (S); 20, 35 & 50 kPa at three installation depths (D) of tensiometer i.e. 20, 30 & 40 cm and a control (traditional practice) were replicated thrice in RCBD. Among all the treatments, highest dry tuber yield was recorded in S₃₅D₂₀ treatment during both the years. This treatment showed significantly higher marketable tuber yield which was statistically at par with S₂₀D₂₀ treatment which had produced highest tuber yield during both the years. Treatment S₃₅D₂₀ registered more than double WUE and WUE_i (averaged over two years) as compared to that of control treatment along saving of 49 % irrigation water. Thus, treatment S₃₅D₂₀ was adjudged the best treatment for irrigation scheduling in the region.

Key words: Furrow-ridge irrigation system, Soil water tension, marketable tuber yield, Tuber dry weight, Water use efficiency

INTRODUCTION:

India is the second largest producer of potatoes after China in the world with 45 million tonnes of potato production, which is 12 % of potatoes produced in the world (Anonymous, 2013a). India has taken a massive stride by doubling its potato production in the last two decades.

Potato seems to be most frequently irrigated among the major winter season crops as furrow irrigation is the most prevalent method of irrigation to potato and the ground water/ canal water is easily available for irrigation purpose under Indo-Gangetic plains. Potato crop requires 7-8 light irrigations under ridge-furrow planting method under North-Western plains of India (Anonymous, 2013b). Earlier studies in the region have shown that water is the most important regulating factor for potato production and precise irrigation scheduling had increased the yield in addition to the increased water use efficiency (Kumar *et al.*, 2007, Kumar *et al.*, 2009, Singh *et al.*, 2012). This crop prefers adequate moisture in the root zone owing to its shallow root system as well as for the maintenance of low soil strength, which are conducive for the development and enlargement of tuber.

The ground water resources are being depleted at fast rate in the North-Western plains of India due to excessive utilization for irrigation purpose. The water scarcities have been forecasted in agriculture and non agriculture sectors with changing climate (Hira, 2009). Moreover, there is increased demand of water for organic and non organic agriculture sector, thereby making it necessary to conduct more research on irrigation schedule on crops.

Tensiometer is a commonly used instrument to determine the soil moisture status by measuring soil matric potential. It symbolizes the force necessary for plant roots to extract

water from the soil. Numerous studies using tensiometers to measure SMP and for scheduling irrigation to potato have been reported (Shae *et al.*, 1999; Kang *et al.* 2004; Wang *et al.* 2007; Wang *et al.* 2011). Medici *et al.* (2014) suggested that irrigated plants should be grown between 10 and 20 kPa SWT and at the maturity stage, a higher SWT (20–35 kPa) might be advisable to improve fruit quality and WUE without the risk of reducing yield.

The previous investigations in the region have mostly used weather based irrigation scheduling, for evaluating soil water availability for the plants (Panigrahi *et al.*, 2001, Kumar *et al.*, 2009, Singh *et al.*, 2010, Singh *et al.*, 2012, Tyagi *et al.*, 2012, Singh and Sood, 2013, Verma *et al.*, 2013. Our efforts were to study the SMP based irrigation scheduling in the region. Thus, it was decided to conduct comprehensive investigation based on SWT for precise irrigation scheduling to the potato crop under furrow-ridge irrigation method. The study was undertaken with an objective to determine the effect of soil matric potential based irrigation scheduling on water use efficiency and tuber yield.

MATERIALS AND METHODS:

Site, climate and soil

The investigation was undertaken on a typic Ustipsamment soil at Vegetable Research Farm, Department of Vegetable Science, Punjab Agricultural University, Ludhiana (Punjab), for two potato growing seasons (October to January) in 2011-12 and 2012-13. The climate of Ludhiana is subtropical, semi-arid with an annual rainfall of 755 mm. Major part of the annual rainfall is concentrated between June to September months and only 50 to 55 mm rainfall occur during the potato growing season (October-January). Soil type was sandy loam with composition of 69 % sand, 19% silt and 12% clay. Some physico-chemical characteristics observed from 15 cm thick soil before the planting of potato were: pH 7.7, electrical conductivity: 0.16 dS m⁻¹, organic C 3.3 g kg⁻¹, 0.5 M NaHCO₃ extractable P (Olsen *et al.*, 1954) 5.75 mg kg⁻¹ and K (Pratt, 1965) 160 mg kg⁻¹ in the year 2011, and pH: 7.9, EC: 0.24 dS m⁻¹, OC: 3.5 g kg⁻¹, extractable P: 8 mg kg⁻¹ and K: 172.5 mg kg⁻¹ during the year 2012. So, it was a low fertility soil. The groundwater table was approximately 50 m below the soil surface.

Table 1: Physical characteristics of soil before planting potato in the year 2011 and 2012.

Soil depth (cm)	Bulk density (g cm ⁻³)		Saturated conductivity (cm hr ⁻¹)		Unsaturated conductivity (cm hr ⁻¹)				Infiltration rate (cm hr ⁻¹)	
					Suction I (2cm)		Suction II (4cm)			
Year	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
0-15	1.40	1.37	305.0	310.0	103.0	104.0	33.5	33.0	6.93	7.03
15-30	1.55	1.51	136.0	140.0	27.0	28.0	11.0	10.0		
30-45	1.60	1.65	143.0	144.0	15.5	14.0	14.0	13.0		
45-60	1.64	1.72	113.0	115.0	25.0	23.0	24.0	22.5		

Experimental design and crop management

Area planned for experiment was pre-irrigated before planting tubers except the control plots. Potato was planted on 18th October and 16th October respectively, during 2011 and 2012. The experiments were conducted in randomized complete block design (RCBD) which was replicated thrice. Plots were measuring 10.0 m × 5.2 m (gross plot size) comprising seven ridges each followed by a furrow, spaced at 60 cm distance during both the years. Pre-sprouted seed tubers with a mean weight of approximately 45 g were planted 0.2 m apart, on ridges separated from each other by 0.6 m (equivalent to a maintaining a plant density of 8.33 plants m⁻²). Two metre wide border was kept between two adjacent plots as well from irrigation channel to prevent unwanted water seepage. Disease free tubers of an early bulking cultivar, Kufri Pukhraj comprised the plant material. Treatments consisted: S₂₀D₂₀, S₃₅D₂₀, S₅₀D₂₀, S₂₀D₃₀, S₃₅D₃₀, S₅₀D₃₀, S₂₀D₄₀, S₃₅D₄₀, S₅₀D₄₀ and a control (traditional/farmers practice), where 'S' is suction/tension level of tensiometers installed in the soil at 'D' depth. Monitoring of dial vacuum gauge tensiometers was started regularly for SMP reading after the complete emergence of the crop which were installed between two plants and in the centre of the ridge in the middle potato row of each plot. Irrigation was applied only when the soil water tension (SWT) reached its targeted value. Standard crop management practices were followed commonly for each treatment as per the PAU package practices for cultivation. Whole phosphorus at the rate of 135 kg ha⁻¹ of Di-ammonium phosphate (18-46-0 NPK), potassium at the rate of 103 kg ha⁻¹ of Potassium chloride (0-0-60 NPK) and 50% nitrogen at the rate of 208 kg ha⁻¹ of Urea fertilizer (46-0-0 NPK) was applied at planting. Remaining 50% Urea fertilizer (46-0-0 NPK) was top dressed 25 days after planting followed by earthing up (operation of putting up soil around the ridge for broadening its base, three to four weeks after planting) of plants. Potato vines were dehaulmed 90 days after planting and tubers were lifted 15 days after dehauling.

Irrigation treatments:

Pre-plant irrigation measuring 5 cm was given to all plots except control plot. All plots received 5 cm of common irrigation after planting, except control plots which received 11 cm irrigation to facilitate the rooting and establishment of the crop for its complete emergence. After this common irrigation, rest irrigation scheduling was done on the basis of soil matric suction as per the treatment requirement. However, the control treatment received first irrigation 10 days after complete emergence and remaining irrigations at an interval of 12 days (Table 2). An extra irrigation was given to control plots in both years during the days when there were chances of frost occurrence. Thus seven irrigations were applied to control plots during both the years. Only rainfall exceeding 5 mm within 25 hr was considered effective and included in the calculations for total water use.

Soil matric potential was measured through 18 dial vacuum gauge tensiometers installed one each in a plot in two replications. The average value of targeted SWT was used to schedule irrigation. The observations of targeted SWT value were started on November, 4 in 2011, and November, 11 in 2012. Tensiometers were examined for its proper functioning before installing in the field. One tensiometer per treatment was installed in two replications in the mid of the two plants in the centre of fourth ridge to avoid edge effects. The soil matric potential readings were observed daily between 8.00 a.m. and 9.30 a.m. to minimize the effect of temperature on the tensiometer reading and irrigation was applied thereafter as per the need. Irrigations in many treatments were delayed when it rained, creating differences between treatments in the total water application in the year, 2012.

Data Collection:

Random samples of 100 g tubers were oven-dried at 65°C until constant weight was attained and further weighed to determine tuber dry weight at harvest. At the time of tuber harvest, 50 plants from each plot were harvested by selecting middle three rows of potatoes during both the years; the tubers were picked manually as marketable tuber yield

The appraisals for dry tuber yield (kg ha^{-1}) were done by multiplying tuber dry weight per 100g with marketable tuber yield. WUE (kg m^{-3}) was calculated as the ratio of dry tuber yield (kg ha^{-1}) to the amount of water ($\text{m}^3 \text{ha}^{-1}$) applied to the crop (supplemental irrigation plus rainfall) during the potato growing season as per the method suggested by Xie *et al.*(2012). The WUE calculated by this method gives an indication of water productivity. While, WUE_i ($\text{kg ha}^{-1}\text{mm}^{-1}$) was calculated as the ratio of marketable tuber yield to the water applied through irrigation.

$$\text{WUE} = \frac{\text{Tuber dry yield}}{\text{Total water applied}}$$

where, total water applied = supplemental irrigation plus rainfall.

$$\text{WUE}_i = \frac{\text{Marketable tuber yield}}{\text{Irrigation water applied}}$$

Meteorological data

Meteorological data were recorded at meteorological station situated about 500 metre distance from the experimental site. Weekly average temperature, relative humidity, sunshine and total rainfall and evaporation were recorded during the potato growing period from 14th October to 27th January for the year 2011-12 and 2012-13 (Fig.1 & Fig. 2).

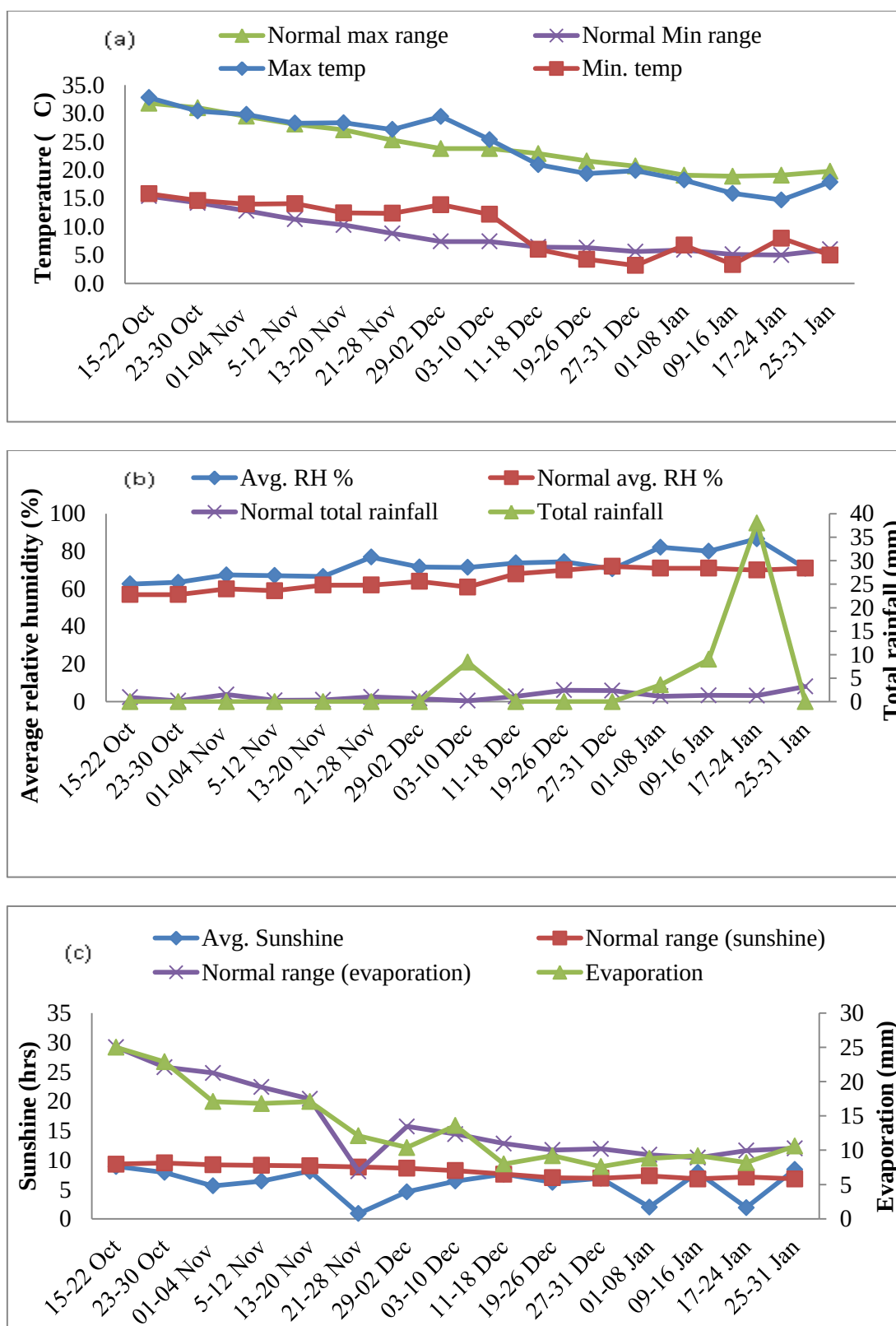


Fig. 1. Maximum and minimum temperature (a), average RH percent & total rainfall (b), average sunshine and total evaporation (c) with their respective average normal range (last 30 years) during the potato growing season 2011-12.

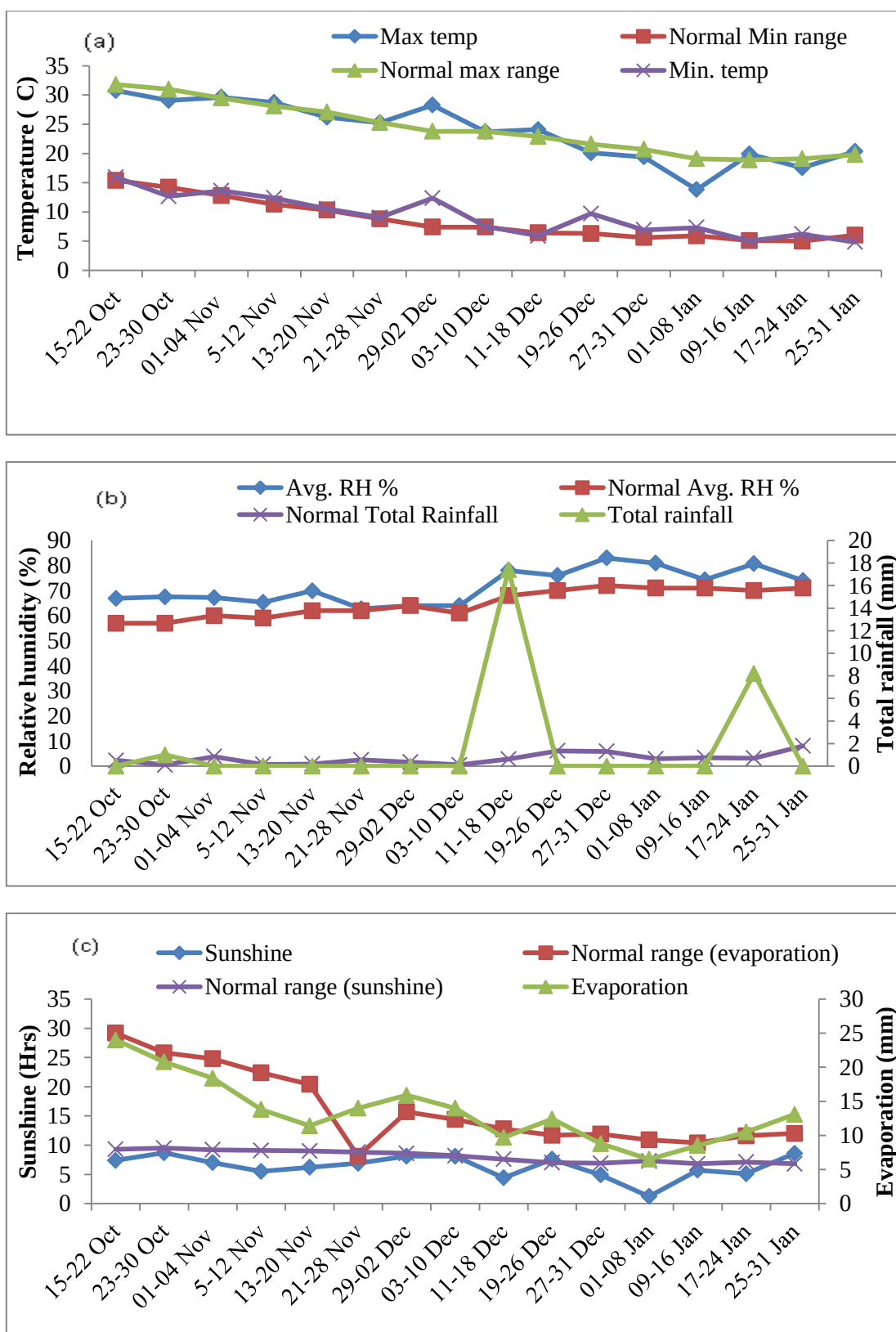


Fig. 2. Maximum and minimum temperature (a), average RH percent & total rainfall (b), average sunshine and total evaporation (c) with their respective average normal range (last 30 years) during the potato growing season 2012-13.

Data Analysis

Two years data were subjected to analysis of variance (ANOVA) (Gomez and Gomez, 2010) based on PROC GLM (SAS software 9.1). Pooled analysis of data for two years was also conducted. Duncan's multiple range tests at $p=0.05$ was applied to compare the means of different treatments.

Temperature, rainfall and evaporation

2011-12: As illustrated in Fig. 1 [(a) to (c)], the average weekly air temperature was higher than that of normal (average of the last 30 years) from 4th November to 9th December but it was lower for rest of the growing period during 2011-12. Average relative humidity remained higher during most of the potato growing season. Total rainfall was not uniformly distributed during the period but it was higher during IInd and IIIrd week of January. There were three events of effective rainfall (above 5mm) which summed up to 55.4 mm. The major portion of rain (38 mm) occurred in the IIIrd week of January (January, 15) which was not of much use to the growth and development because potato plants were in late maturity stage as dehauling was done on 16th of January. Thus, rainfall of 17.4 mm was considered as effective precipitation for further calculations purpose. Average sunshine remained considerably lower as compared to normal data. Total evaporation remained lower compared to normal data during the period under consideration.

2012-13: During the 2012-13 potato growing period [Fig. 2: (a) to (c)], the average temperature did not vary significantly except during 1st and 2nd week of January when it was comparatively lower than the normal data. Total rainfall was not uniformly distributed and was lower than the normal range. There were two events of effective rainfall measuring 17.4 mm and 8.2 mm of water in the IIIrd week of December and IIIrd week of January. But the second event of rainfall occurred after dehauling of potato vines. Thus, only 17.4 mm of rainfall was considered for further calculation purpose. Average humidity and average sunshine hrs followed the trend of previous year although the sunshine hours showed less divergence from normal as compared to previous year. The average sunshine hours were comparatively higher than the previous year. Total evaporation remained lower compared to normal except a few incidences when it was higher than the normal.

RESULT AND DISCUSSION

Irrigation water application and soil water tension dynamics

The number and amount of irrigation for different treatments during the potato growing seasons are shown in Table 2. The depth of water for each irrigation event of treatments was constantly changing during the growing season from 45 to 46 mm, the

corresponding change was from 57.5 to 60 mm for control. The targeted values of tensiometer recording were started at uniform moisture storage in all the treatments (data not shown). The irrigation amount received after complete crop emergence by different treatments varied as shown in the table 2. One major event of effective rainfall during the active growth of crop (December, 2012) disturbed the targeted potentials on the corresponding days, thus less irrigation water was supplied to $S_{35}D_{20}$, $S_{50}D_{20}$, $S_{35}D_{30}$, $S_{50}D_{30}$, and $S_{20}D_{40}$ treatments during 2012. The treatment $S_{50}D_{40}$ received least amount of water during both the years due to lower SMP. Our results are consistent with the findings of Wang *et al.* (2011), they also reported application of lower amount of irrigation water at lower SMP. The control had received highest amount of irrigation water and experienced poor soil aeration, which may ultimately have affected overall plant performance.

Water use efficiency (WUE) and Irrigation water use efficiency (WUE_i)

There was an increase in WUE ca. 186% and 183% in $S_{50}D_{40}$ and $S_{50}D_{30}$, respectively increased, with a corresponding water saving of 70% and 62 % than that of control during the year 2011 (Table 2). During the year 2012, $S_{50}D_{30}$ increased WUE by 218%, with a water saving of 69% which was followed by $S_{50}D_{20}$ showing 186% increase in WUE along with and 61% water saving. The check treatment (control) recorded lowest WUE due to highest amount of water volume consumed by control i.e. 5474 and 5299 m³ ha⁻¹ during first and second year. The WUE in $S_{35}D_{20}$ was upto 177% higher than control when data was pooled over two years. The analysis of pooled data revealed that WUE followed the order of $S_{50}D_{30} > S_{50}D_{20} > S_{50}D_{40} > S_{35}D_{20} > S_{35}D_{30} > S_{35}D_{40} > S_{20}D_{40} > S_{20}D_{30} > S_{20}D_{20} > \text{control}$. The first treatment was significantly higher among all the treatments and next five treatments in the order were statistically at par with each other. Similar trends of higher water use efficiency with the use of lower volume of water were also obtained by Xie *et al.* (2012) in China.

The similar trends as for WUE were recorded for WUE_i. Treatments $S_{50}D_{30}$ and $S_{50}D_{40}$ recorded highest WUE_i followed by $S_{35}D_{20}$ in 2011. While, $S_{50}D_{30}$ recorded highest WUE_i followed by $S_{50}D_{20}$ and $S_{35}D_{20}$ in the year 2012. Similar to WUE, lowest values of WUE_i were recorded in the control during both the years. $S_{35}D_{20}$ recorded 105 and 147% higher WUE_i than that of control treatment in 2011 and 2012, respectively. Approximately similar range of WUE was obtained by Wang *et al.* (2011) except for the lowest value obtained in our experiment for the control treatment. The values of WUE obtained by Kang *et al.* (2004) was higher than values of WUE_i obtained in our investigation which may be due to less irrigation water consumed under drip irrigation system. The WUE (30.2 to 58.4 kg ha⁻¹ mm⁻¹) obtained by Panigrahi *et al.* (2001) was lower than WUE_i in our experiment because they had obtained lower tuber yield in their study.

Table 2: Number of irrigations, average water application per irrigation, seasonal total irrigation depth, total water application ($\text{m}^3 \text{ ha}^{-1}$), water use efficiency ($\text{kg tuber dry weight m}^{-3}$ of water applied) and Irrigation water use efficiency (WUE_i) for different treatments during 2011 and 2012 plantings.

Treatments	Pre-plant irrigation + Crop establishing irrigation	Number of irrigations		Average irrigation application (mm)		Seasonal irrigation application (mm)		Water volume ($\text{m}^3 \text{ ha}^{-1}$) (seasonal irrigation application + total rainfall)			WUE ($\text{kg tuber dry weight m}^{-3}$ of water volume)			WUE _i ($\text{kg ha}^{-1} \text{mm}^{-1}$)		
Year	2011 & 2012	2011	2012	2011	2012	2011	2012	2011	2012	Average	2011	2012	Pooled	2011	2012	Pooled
S ₂₀ D ₂₀	50mm+50 mm	5	5	45.5	45.0	227.5	225.0	3449	3424	3436.5	0.94d	1.04f	0.99c	63.4d	68.0d	65.7f
S ₃₅ D ₂₀	50 mm +50 mm	4	3	45.5	45.0	182.0	135.0	2994	2524	2759.0	1.14abc	1.49bc	1.32abc	71.7abc	91.8b	81.8bc
S ₅₀ D ₂₀	50 mm +50 mm	3	2	45.0	45.0	135.0	90.0	2524	2074	2299.0	1.23ab	1.60b	1.42ab	74.7ab	96.1b	85.4b
S ₂₀ D ₃₀	50 mm +50 mm	4	4	45.0	45.4	180.0	181.6	2974	2990	2982.0	1.06bcd	1.12ef	1.09bc	66.9cd	67.9d	67.4f
S ₃₅ D ₃₀	50 mm +50 mm	3	2	45.0	45.0	135.0	90.0	2524	2074	2299.0	1.14abc	1.48bc	1.31abc	69.5bcd	88.4b	78.9cd
S ₅₀ D ₃₀	50 mm +50 mm	2	1	45.0	45.0	90.0	45.0	2074	1624	1849.0	1.30a	1.78a	1.54a	78.1a	106.4a	92.2a
S ₂₀ D ₄₀	50 mm +50 mm	4	3	45.0	45.5	180.0	136.5	2974	2539	2756.5	1.03cd	1.28de	1.15bc	63.9d	77.9c	70.9ef
S ₃₅ D ₄₀	50 mm +50 mm	2	2	45.0	46.0	90.0	92.0	2074	2094	2084.0	1.23ab	1.28de	1.25abc	73.8ab	74.3cd	74.0de
S ₅₀ D ₄₀	50 mm +50 mm	1	1	45.5	45.0	45.5	45.0	1629	1624	1626.5	1.32a	1.39cd	1.36ab	78.0a	80.3c	79.1cd
Control	0 +110 mm	7	7	60.0	57.5	420.0	402.5	5474	5299	5386.5	0.46e	0.56g	0.51d	34.9e	37.2e	36.1g
p-value	-			-	-			-	-	-	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Column mean with different letters differ significantly at p-value <0.05. ** The effective total rainfall during both the planting seasons was 17.4mm.

Table 3: Average tuber weight (g) and marketable tuber yield (q ha⁻¹) Tuber dry weight (g per 100 g of fresh weight), dry tuber yield (kg ha⁻¹) for different treatments for potato plantings in the year 2011 and 2012.

Treatment	Average tuber weight (g)			Marketable tuber yield (q ha ⁻¹)			Tuber dry weight (g per 100 g)			Dry tuber yield (kg ha ⁻¹)		
Year	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Average
S ₂₀ D ₂₀	50.6a	53.2a	51.9ab	207.5a	220.9a	214.2a	15.6cd	16.1bc	15.9cd	3243.9	3556.5	3400.2
S ₃₅ D ₂₀	49.9a	51.8ab	50.9abc	202.3ab	215.7ab	209.0ab	16.8bc	17.5ab	17.2bc	3402.0	3774.2	3588.1
S ₅₀ D ₂₀	44.8ab	45.1abc	45.0cde	175.5cd	182.5de	179.0cd	17.7abc	18.2a	18.0ab	3112.2	3321.5	3216.9
S ₂₀ D ₃₀	46.7ab	47.2abc	47.0abcd	187.4bc	191.1cd	189.3c	16.8bc	17.5ab	17.2bc	3155.1	3344.8	3250.0
S ₃₅ D ₃₀	43.5ab	43.1bcd	43.3de	163.3d	167.9ef	165.6de	17.6abc	18.3a	18.0ab	2879.5	3072.6	2976.1
S ₅₀ D ₃₀	40.6bc	40.4cd	40.5de	148.4e	154.2fg	151.3ef	18.2ab	18.8a	18.5ab	2695.9	2899.6	2797.8
S ₂₀ D ₄₀	45.5ab	46.4abc	46.0bcd	178.8cd	184.1d	181.5cd	17.0abc	17.7ab	17.4abc	3046.1	3259.2	3152.7
S ₃₅ D ₄₀	39.8bc	38.5cd	39.2ef	140.2e	142.6g	141.4f	18.2ab	18.8a	18.5ab	2551.6	2680.9	2616.3
S ₅₀ D ₄₀	33.8c	33.5d	33.7f	113.4f	116.5h	115.0g	19.0a	19.3a	19.1a	2150.6	2252.1	2201.4
Control	51.1a	54.2a	52.7a	185.1c	203.1bc	194.1bc	14.2d	15.5c	14.9d	2539.0	2954.3	2746.7
p-value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	-	-	-

* Column mean with different letters differ significantly at p-value <0.05.

Marketable tuber yield and average tuber weight

Treatment S₂₀D₂₀ produced higher 6.5% marketable tuber yield in 2011 as compared to in the year 2012 and the corresponding rate for S₃₅D₂₀ was 6.6% (Table 3). Both of these treatments were targeted at lower soil water suction measured in the upper soil layer as compared to the other treatments. The pooled analysis of data also showed that treatments S₂₀D₂₀ and S₃₅D₂₀ recorded 86% and 82% higher marketable tuber yield compared to the control. The marketable tuber yield for control treatment followed these two best treatments. This was in fact reasonable because this treatment had received the highest amount of irrigation water. In S₅₀D₄₀ treatment, lowest SWP was measured at 0.4 m soil depth and it had received lowest amount of water volume during both the years. The tuber growth was restrained under this treatment which may probably due to soil moisture deficit in the of root zone area. Our result agree with the findings of Wang *et al.* (2007). Kang *et al.* (2004) also found that there was continuous decrease in the tuber yield as the soil matric potential increased from -25 kPa to -55 kPa. It was seen that potato yield decreased with the drop in SMP from -20 kPa to -50 kPa at all the installation depths of tensiometer.

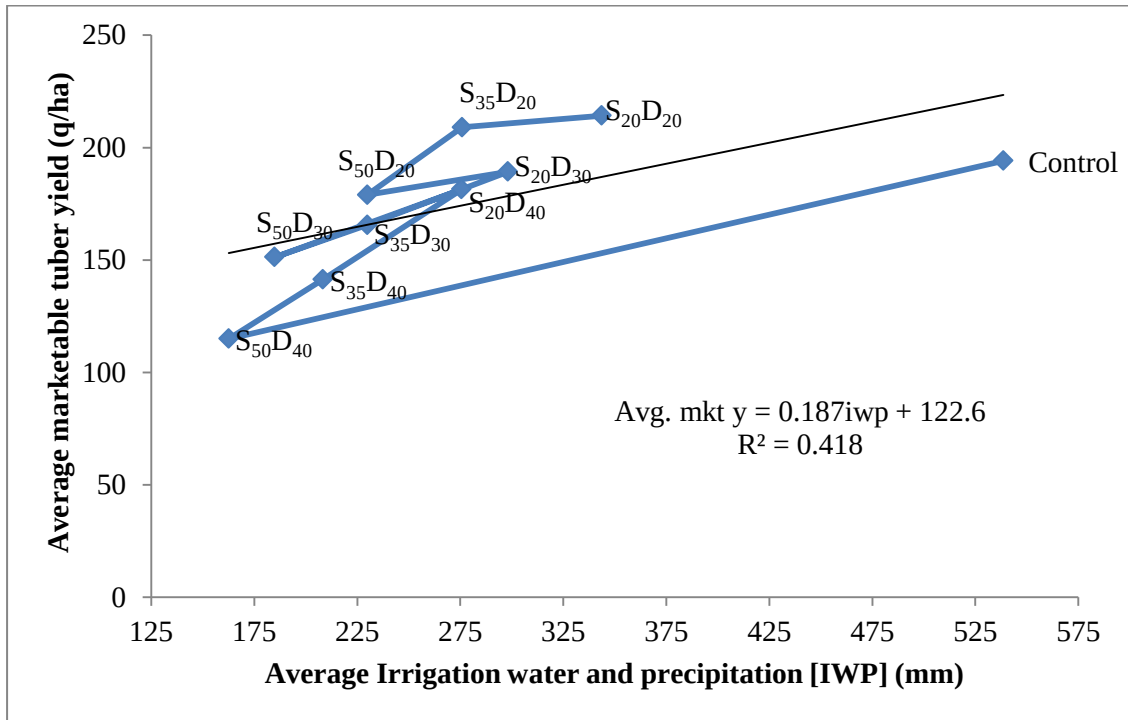


Fig.3. Relationship between marketable tuber yield (average of year 2011 & 2012) and Irrigation water applied (average of year 2011 & 2012) for different treatments.

The relationship between the average marketable tuber yield (avg. mkt y) and total irrigation water applied (sum of Irrigation water and precipitation = iwp) for different treatments (Fig. 3) is given by the equation

$$\text{Avg. mkt y (q/ha)} = 0.187 \text{ iwp (mm)} + 122.6$$

The value of coefficient of determination between these two variables was found to be 0.418. It was observed that the marketable tuber yield increase with increase in irrigation water application. The relationship between the marketable tuber yield and water use efficiency is shown in Fig. 4. In general, the higher values of water use efficiency correspond to lower marketable tuber yield and *vice versa*. Higher marketable tuber yields and water use efficiency were recorded in $S_{35}D_{20}$ and $S_{20}D_{20}$ as compared to the control plot over the two years. The water use efficiency obtained under $S_{35}D_{20}$ and $S_{20}D_{20}$ was about double as compared to the control. Thus, our results suggest that lower SMP of -35 kPa maintained in upper soil depth of 20 cm enhance WUE and maintain tuber yield along with saving of 49% irrigation water.

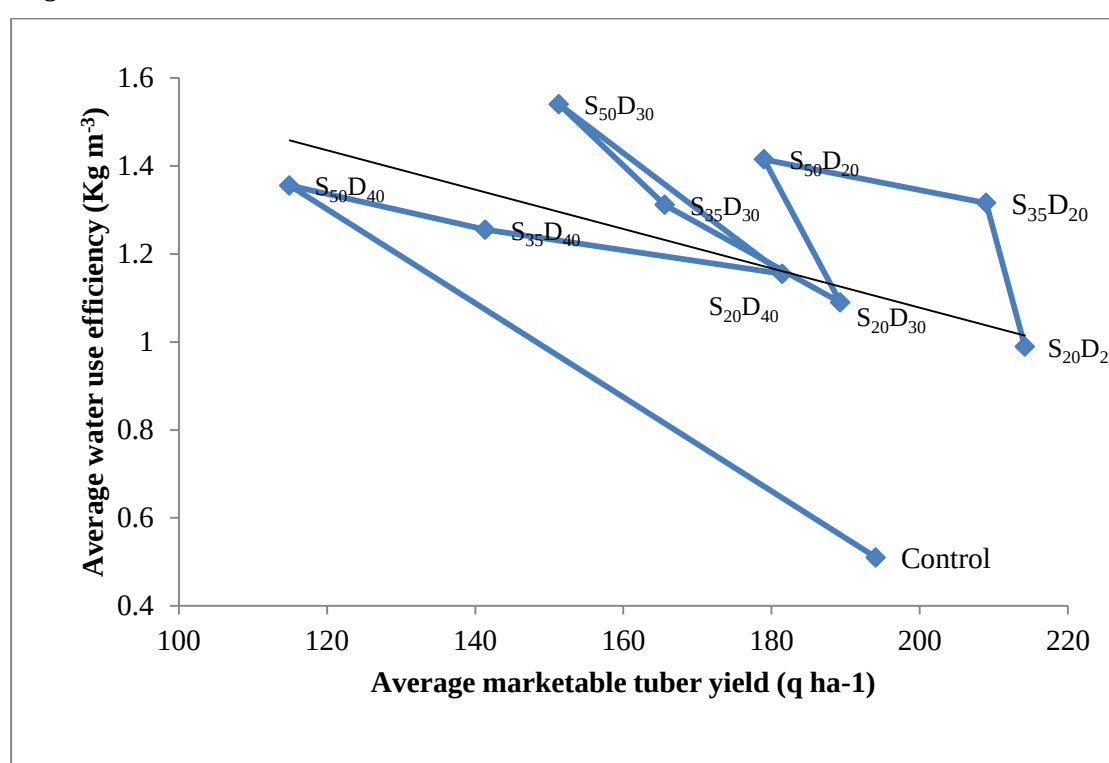


Fig.4. Relationship between marketable tuber yield (average of 2011 & 2012) and water use efficiency (average of 2011 & 2012) for different treatments.

Tuber dry weight and dry tuber yield

The treatment $S_{50}D_{40}$ registered highest tuber dry weight (per 100g of fresh weight) during both the years. It was followed by treatments $S_{35}D_{40}$ and $S_{50}D_{30}$ during same period (Table 3). When further analysis of pooled data was conducted it was found that all the treatments except $S_{20}D_{20}$, and control were statistically at par with each other. Minimum tuber dry weight was recorded under control during both the years which may probably be due to higher percent of water present in the tubers in this treatment as compared to other treatments. While, highest tuber dry weight in $S_{50}D_{40}$ indicated presence of lower quantity of water in the

tubers. Dry tuber yield was computed from the multiple of tuber dry weight and marketable tuber yield. Dry tuber yield was increased by 34%, 28%, 24%, and 22% in 2011, and 28%, 20%, 13%, and 12% in 2012, respectively, for $S_{35}D_{20}$, $S_{20}D_{20}$, $S_{20}D_{30}$ and $S_{50}D_{20}$.

Thus, maintaining higher SMP in upper soil layer is important for $S_{20}D_{20}$ and $S_{35}D_{20}$ (-20 kPa and -35 kPa at 20cm soil depth) treatments which gave higher marketable tuber yield. These treatments were followed by $S_{20}D_{30}$ treatment which belonged to SMP of -20 kPa at 30 cm soil depth for both of the variables.

$S_{35}D_{20}$ registered more than double WUE as compared to farmers practice (control). So based on higher value of WUE, treatment $S_{35}D_{20}$ is showing edge over other treatments. This treatment was also better over other treatments in terms of tuber quality and yield in addition to the medium saving of irrigation water. Although, average volume of water used in $S_{50}D_{40}$ ($1626.5 \text{ m}^3 \text{ ha}^{-1}$) and $S_{50}D_{30}$ ($1849.0 \text{ m}^3 \text{ ha}^{-1}$) was much lower than its usage in $S_{35}D_{20}$ ($2759 \text{ m}^3 \text{ ha}^{-1}$) treatment. Highest saving of 70% irrigation water was recorded in the $S_{50}D_{40}$ treatment followed by $S_{50}D_{30}$ (66%) as compared to traditional irrigation practice. But, due to continuous soil moisture deficit the tuber yield was drastically reduced in the $S_{50}D_{40}$ and $S_{50}D_{30}$ treatments probably in the present investigation. The treatment utilized 49% less irrigation water as compared to the traditional irrigation practice in the region. The irrigation schedule of $S_{35}D_{20}$ treatment created optimum soil environmental conditions for tuber growth and development through better water and nutrient uptake. While, delayed irrigation at higher SWT for treatments $S_{50}D_{20}$, $S_{50}D_{30}$, and $S_{50}D_{40}$ may had caused lower soil moisture content in the root zone resulting in poor tuber growth and development. Light irrigations for maintaining lower soil moisture tension in upper soil layer ($S_{35}D_{20}$) was better than the frequent and heavier irrigations as practised by the farmers which lead to reduced WUE.

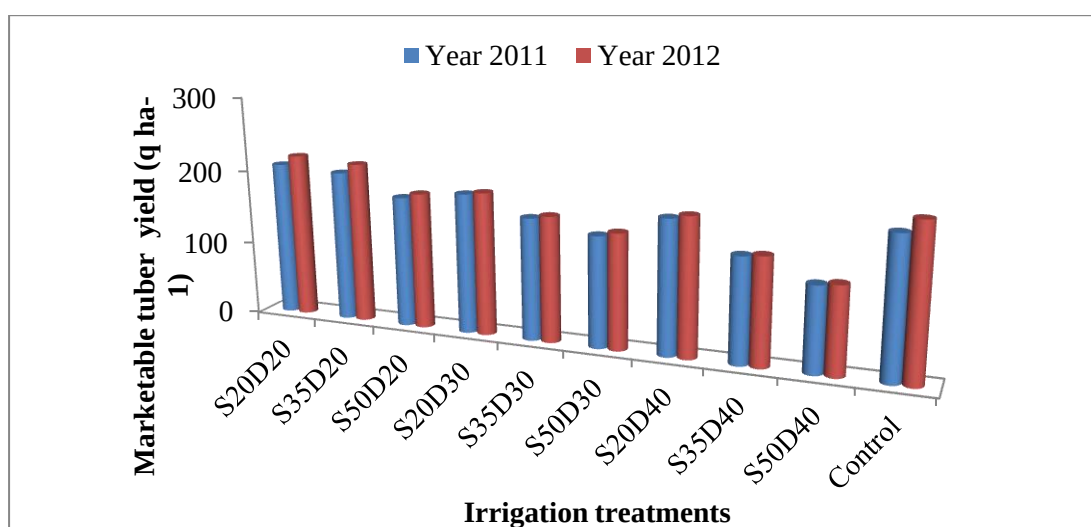


Fig. 5. Comparative marketable tuber yield (q ha^{-1}) for potato plantings in the year 2011 and 2012.

The analysis of growth and yield parameters showed that tuber dry weight, and marketable tuber yield (Fig. 5) was on higher side during the year 2012 as compared to the year 2011. Variation in yield in the successive years for same crop cultivar has also been reported by Ferreira and Goncalves (2007) and Shahnazari *et al.* (2008). The difference obtained in our study may be attributed to better sunshine hrs during the planting year of 2012 [Fig. 2 (c)] as compared to the year 2011 [Fig. 1 (c)]. The sunshine hours were reduced to zero during higher number of days in November, December, 2011 and January, 2012 as compared to the planting season of 2012-13.

Thus, our results indicated that the lower soil moisture tension of 35 kPa in the upper 20 cm soil layer (S₃₅D₂₀) has resulted in enhanced tuber growth and development along with medium saving of irrigation water. This treatment recorded higher marketable tuber yield, WUE and WUEi among all other treatments tested. Adopting this threshold relates to 3 to 4 irrigations of 45 to 45.5 mm each depending on the rainfall during potato growing period. Two additional irrigations of 50 mm each were applied, first as pre-irrigation and second irrigation to substantiate emergence. Thereafter, the application of single irrigation, two weeks after the complete emergence of crop and remaining 2-3 irrigations at 17 days interval may enhance WUE and save 49% irrigation water as compared to the traditional irrigation practice. The soil moisture deficit under all the tested soil depths at higher soil moisture tension of 50 kPa had resulted in poor crop growth and development. Soil moisture tension of 50 kPa at 40 cm soil depth showed the highest reduction in the crop growth and tuber yield implying water stress conditions. Traditional irrigation practice had received highest quantity of water among all the treatments which may have caused more than optimum soil water in the root zone resulting in reduced water and nutrient uptake owing to decreased soil aeration as well as tuber health deterioration in this treatment.

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SCHEDULING IRRIGATION TO POTATO BASED ON SOIL MATRIC POTENTIAL CRITERION UNDER NORTH-WESTERN INDIAN PLAINS

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Abstract: A field investigation was conducted in sandy loam soil for two potato growing seasons (October to January) during 2011-12 and 2012-13 with the objective to standardize the appropriate soil matric potential along with its depth of measurement under furrow-ridge irrigation system. Three levels of soil matric suction (S) ; 20, 35 & 50 kPa at three installation depths (D) of tensiometer i.e. 20, 30 & 40 cm and a control (traditional practice) were replicated thrice in RCBD. Highest dry tuber yield was recorded in S₃₅D₂₀ treatment during both the years. Significantly higher marketable and graded tuber yield with lower discarded percent was recorded under S₂₀D₂₀ which was statistically at par with S₃₅D₂₀ treatment in both the years. Analysis of pooled data for marketable and graded tuber yield, average tuber weight, discarded percent of tubers, root dry weight, plant height at harvest and above ground dry matter accumulation 30, 60 DAP and at harvest also favoured both S₃₅D₂₀ and S₂₀D₂₀ treatments. However averaged over two years, WUE and WUE_i of S₃₅D₂₀ was more than double that of control treatment along with higher marketable tuber yield as 49 % irrigation water was saved. Our results revealed that treatment S₃₅D₂₀ was the best treatment for irrigation scheduling in the region. Thus, our results suggest that tensiometer placed at 20 cm depth in the centre of ridge between the potato plants and by maintaining SMP of -35 kPa was being favourable setting for potato production and can be effectively used for scheduling irrigation to potato. Adopting this threshold corresponded to applying single irrigation two weeks after the complete emergence of crop and remaining 2-3 irrigations at 17 days interval depending on the effective rainfall.

Key words: Above ground dry matter accumulation, Furrow-ridge irrigation system, Soil water tension, Source to sink ratio, Water use efficiency

1.0 Introduction: Globally India is the second largest producer of potato after China (Scott and Suarez, 2011). Its estimated production is 45.3 million tonne from 1.90 million ha in India (<http://faostat3.fao.org/>, 2013). Potato has emerged as an important food crop in the Indo-Gangetic plains of India. Furrow irrigation is the most prevalent method of irrigation to potato under Indo-Gangetic plains of India as the ground water/ canal water is easily available for irrigation purpose. However, the ground water resources are being depleted at faster rate in the North-Western plains of India due to its excessive utilization for irrigation purpose. Additionally, the water scarcities in agriculture are being projected in the light of agriculture, climate change and competition from non agriculture sectors (Hira, 2009).

Irrigation consumes the maximum amount of energy among all the field operations for potato production (Gulati and Singh, 2011). Potato consumes 500 to 700 mm of water in 120 to 150 days long life cycle (www.potato2008.org). The crop prefers wet moisture regime

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not only for adequate moisture owing to its shallow root system but also for maintenance of low soil strength, which are conducive for the development and enlargement of tuber. It seems to be most frequently irrigated among the major winter season crops under North Indian conditions. Potato crop requires 7-8 light irrigations under ridge-furrow planting method under North-Western plains of India (Anonymous, 2013). Moreover, farmers of the area in anxiety for higher yield apply water either frequently or heavily at an interval of 4 to 12 days, most of which is lost as deep percolation along with soil nutrients besides limiting soil aeration. Studies in the region have shown that water is the most important regulating factor for potato production and precise irrigation scheduling had shown increase in its growth and yield in addition to the increased water use efficiency (Kumar et al., 2007, Kumar et al., 2009, Singh et al., 2012).

Several options are available for precise irrigation scheduling to crops (Shock and Wang, 2011). One option is to schedule irrigations based on the measurement of soil water content or soil water tension (SWT). When a soil water tension irrigation criterion is combined with the knowledge of the soil water holding capacity, a planned increment of water can be applied at the right time, reducing the off-site effects of water movement (Shock and Wang, 2011). Tensiometer is an instrument used to determine soil moisture status by measuring soil matric potential. It symbolizes the force necessary for plant roots to extract water from the soil. Kukal et al.(2005) had successfully used soil matric potential as basis for scheduling irrigation to rice crop in North Western plains of India with 25-30 per cent saving in irrigation water. Numerous studies using tensiometers to measure SMP and for scheduling irrigation to potato have been reported: kang et al.(2004), investigated five regimes ranging between 15 to 55 kPa SWT in loam soil for potato using drip irrigation, highest yield and WUE with threshold of 25 kPa was obtained with an irrigation frequency of once a day. Similarly, Wang et al.(2007) concluded that potato plant height, tuber bulk rate and grade, water use efficiency and Irrigation water use efficiency was the highest under soil matric potential of -25 kPa, while -15 kPa was too high and -45 kPa led to severe water stress. They suggested that tensiometer placed beneath the drip emitter at 20 cm depth may be effectively used for scheduling irrigation to potato under drip irrigation system. Wang et al.(2011) reported that highest WUE, yield and tuber quality was obtained with -25 kPa during tuber initiation and growth and -35 kPa soil matric potential during tuber maturation. However, drip irrigation threshold of -35 kPa SMP at all growth stages caused water stress for potato growth and development in the arid area. On reviewing several studies on different crops, Medici et al.(2014) generalized the statement that irrigated plants should be grown between 10 and 20 kPa SWT to achieve the highest combination of yield and WUE. At the maturity stage, a higher SWT (20–35 kPa) might be advisable to improve fruit quality and WUE without the

risk of reducing yield. It was reported by the Medici and his co-workers that there is need for further conducting research on the basis of soil water tension for irrigation scheduling to crops.

The irrigation scheduling based on the soil matric potential has been viewed as better criterion for many crops including potato, but the information and work is lacking in the region. The previous investigators in the region have mostly used weather based scheduling, for evaluating soil water availability for the plants and not SWT for irrigation scheduling to potato (Panigrahi et al., 2001, Kumar et al., 2009, Singh et al., 2010, Singh et al., 2012, Tyagi et al., 2012, Singh and Sood, 2013, Verma et al., 2013). Moreover, the work on irrigation scheduling based on the soil matric potential under furrow irrigation method in potato is lacking. Thus, it necessitated for conducting comprehensive investigation based on SWT for precise irrigation scheduling to the potato crop in the region. Therefore, a study was planned for scheduling irrigation based on soil matric potential under furrow-ridge irrigation method under North-Western India with an objective to determine the most appropriate depth for installation of tensiometer and suitable soil matric potential for higher tuber yield and water use efficiency.

2.0 Material and Methods:

2.1. Site, climate and soil

The investigation was undertaken on a typical Ustipsamment soil at Vegetable Research Farm, Department of Vegetable Science, Punjab Agricultural University, Ludhiana (Punjab), India (30° 53' N, 75° 49' E) for two potato growing seasons (October to January) in 2011-12 and 2012-13. The climate of Ludhiana is subtropical, semi-arid with an annual rainfall of 755 mm. Major part of the annual rainfall is concentrated between June to September months. Only 50 to 55 mm rainfall occur during the potato growing season (October-January). The mean monthly temperatures during the potato growing season varied from 11 to 24.3°C. Soil type was sandy loam with composition of 69 % sand, 19% silt and 12% clay. Some physico-chemical characteristics observed from 15 cm thick soil before the planting of potato in 2011 were: pH 7.7, electrical conductivity: 0.16 dS m⁻¹, organic C 3.3 g kg⁻¹, 0.5 M NaHCO₃ extractable P (Olsen et al., 1954) 5.75 mg kg⁻¹, K (Pratt, 1965): 160 mg kg⁻¹ and pH: 7.9, EC: 0.24 dS m⁻¹, OC: 3.5 g kg⁻¹, extractable P: 8 mg kg⁻¹ and K: 172.5 mg kg⁻¹ during the year 2012. So, it is a low fertility soil. The groundwater table is approximately 50 m below the soil surface. The bulk density, saturated hydraulic conductivity and unsaturated hydraulic conductivity (Smettem and Clothier, 1989) were measured using disc permeameter (Table 1) during 2011 and 2012 before the commencement of experiment.

2.2. Experimental Design

Area planned for experiment was pre-irrigated before planting tubers except the control plots. Potato was planted on 18th October and 16th October respectively, during 2011 and 2012. The experiments were conducted in randomized complete block design (RCBD) replicated thrice. Plots measuring 10.0 m × 5.2 m (gross plot size) comprising seven ridges each followed by a furrow, spaced at 60 cm were planted during both the years. Two metre wide border was kept between two adjacent plots as well from irrigation channel to prevent unwanted water seepage. An early bulking cultivar, Kufri Pukhraj comprised the plant material. Treatments include: ten treatments involving three levels of soil water tension/suction (20 kPa, 35 kPa, 50 kPa) at three installation depths of tensiometer (20 cm, 30 cm and 40 cm) and a control (traditional practice) thus comprising S₂₀D₂₀, S₃₅D₂₀, S₅₀D₂₀, S₂₀D₃₀, S₃₅D₃₀, S₅₀D₃₀, S₂₀D₄₀, S₃₅D₄₀, S₅₀D₄₀ and a control. Monitoring of tensiometers was started regularly for SMP reading after the complete emergence of the crop. Irrigation was applied only when the soil water tension (SWT) reached its targeted value. A performa was prepared and filled after polling and personal interviews with the farmers for collecting information regarding crop and irrigation management practices followed by them before finalizing irrigation scheduling for control treatment. Dial vacuum gauge tensiometers were installed at specified depth for different treatments, between two plants and in the centre of the ridge in the middle potato row of each plot.

2.3. Crop management

Disease free and pre-sprouted seed tubers with a mean weight of approximately 45 g were planted 0.2 m apart on top of the ridges, in rows separated from each other by 0.6 m (equivalent to a maintaining a plant density of 8.33 plants m⁻²). Before planting potato tubers were dipped in fungicide (Monceron 0.25%) solution for 10 minutes and spread thereafter under shade for drying. All plants emerged 18 and 21 days after planting during the first and second years respectively. Standard crop management practices were followed uniformly for all the treatments. Fertilizer was applied on the basis of soil test and as per the recommendations of Punjab Agricultural University, Ludhiana. Whole phosphorus at the rate of 135 kg ha⁻¹ of Di-ammonium phosphate (18-46-0 NPK), potassium at the rate of 103 kg ha⁻¹ of Potassium chloride (0-0-60 NPK) and 50% nitrogen at the rate of 208 kg ha⁻¹ of Urea fertilizer (46-0-0 NPK) was applied at planting. Remaining 50% Urea fertilizer (46-0-0 NPK) was top dressed 25 days after planting followed by earthing up. Potato vines were dehaulmed 90 days after planting and tubers were lifted 15 days after dehaulming. Thus, crop was harvested on 31 January 2012 and 29 January 2013. Periodic observations for growth and yield were recorded at 30, 60 DAP (days after planting) and at harvest.

2.4. Irrigation treatments:

Good quality irrigation water (EC: 0.5 dS m⁻¹) was sourced from the tube-well installed near the experimental area. Pre-plant irrigation measuring 5 cm was given to all plots except control plot which received 11 cm irrigation after planting. All plots received 5 cm of common irrigation after planting to facilitate the rooting and establishment of the crop for its complete emergence. After this common irrigation, rest irrigation scheduling was done on the basis of soil matric suction as per the treatment requirement. However, the control treatment received first irrigation 10 days after complete emergence and remaining irrigations at an interval of 12 days (Table 3). Only rainfall exceeding 5 mm within 25 hr was considered effective and included in the calculations for total water use.

Soil matric potential was measured through dial vacuum gauge tensiometers installed one each in a plot. The average value of targeted SWT was used to schedule irrigation. The observations of targeted SWT value were started on November, 4 in 2011, and November, 11 in 2012. Tensiometers were examined for its proper functioning before installing in the field. A hole was made in the soil up to 20, 30 and 40 cm depth having a diameter slightly larger than that of the tensiometer tip. Before inserting tensiometers vertically, soil water slurry was put into the dugout holes as per the method suggested by Kukal et al. (2005). One tensiometer per treatment was installed in two replications in the mid of the two plants in the centre of fourth ridge to avoid edge effects. The soil matric potential readings were observed daily between 8.00 a.m. and 9.30 a.m. and irrigation was applied thereafter as per the need. Irrigations in many treatments were delayed when it rained, creating differences between treatments in the total water application in the year, 2012.

2.5. Data Collection:

Five plants were chosen and marked from each plot at 30, 60 DAP and at the time of harvest for recording plant height and above ground dry matter accumulation. Plants were harvested manually and separated into above-ground and below ground biomass at harvest to record plant, root and tuber growth. Samples of above-ground biomass and tubers were oven-dried at 65°C until constant weight was attained and further weighed to determine above ground dry matter accumulation and tuber dry weight at harvest. Leaf area index (LAI) was recorded 60 DAP using Sun Scan canopy analyzer (Delta T-Devices Ltd., UK). Dry root weight was measured indoors after the root samples were oven-dried at 60°C for 24 hrs.

At tuber harvest, 50 plants from each plot were harvested by selecting middle three rows of potatoes during both the years; the tubers were picked manually, counted, graded based on the tuber weight. Tuber fresh weight was taken to determine marketable tuber yield, graded tuber yield and average tuber weight. There were four classes based on the size of tubers: large (>100g), medium (75 to 100g), small (50 to 75g) and smaller (15 to 50g).

Deformed and diseased tubers and tubers that weighed <15 g were also counted and weighed together and were considered blemished tubers. Tubers showing greening were counted separately and weighed and considered as green tubers. Discarded production was determined as total sum of blemished and green tubers.

The appraisals for dry tuber yield (kg ha^{-1}) were done by multiplying tuber dry weight per 100g with marketable tuber yield. WUE (kg m^{-3}) was calculated as the ratio of dry tuber yield (kg ha^{-1}) to the amount of water ($\text{m}^3 \text{ha}^{-1}$) applied to the crop (supplemental irrigation plus rainfall) during the potato growing season as per the method suggested by Xie et al.(2012). It gives an indication of water productivity. While, WUE_i ($\text{kg ha}^{-1}\text{mm}^{-1}$) was calculated as the ratio of marketable tuber yield to the water applied through irrigation. The source/sink ratio is the ratio of dry canopy weight measured when maximum leaf area index (75 DAP during both the years) was achieved and the tuber dry weight measured at the end of the crop cycle as per the method used by Ierna and Mauromicale, 2012.

2.6. Meteorological data

Meteorological data were recorded at meteorological station situated about 500 metre distance from the experimental site. However, non recording rain gauge was fixed at experimental site to measure rainfall. Weekly average temperature, relative humidity, sunshine and total rainfall and evaporation were recorded during the potato growing period from 14th October to 27th January for the year 2011-12 and 2012-13 (Fig. 1 & Fig. 2).

2.7. Data Analysis

Two years data were subjected to analysis of variance (ANOVA) (Gomez and Gomez, 2010) based on PROC GLM (SAS software 9.1). Duncan's multiple range tests at $p=0.05$ was applied to compare the means of different treatments. Before ANOVA, percentage data of discarded, green and blemished production were transformed into angular values by using $\arcsin\sqrt{\%}$. The values of these variables given in the Table are actual values.

2.8. Temperature, rainfall and evaporation

2011-12: As illustrated in Fig. 1 [(a) to (d)], the average weekly air temperature was higher than that of normal (average of the last 30 years) from 4th November to 9th December but it was lower for rest of the growing period during 2011-12. Average relative humidity remained higher during most of the potato growing season. Total rainfall was not uniformly distributed during the period but it was higher during IInd and IIIrd week of January. There were three events of effective rainfall (above 5mm) which summed up to 55.4 mm. The major portion of rain (38 mm) occurred in the IIIrd week of January (January, 15) which was not of much use to the growth and development because potato plants were in late maturity stage as dehauling was done on 16th of January. Thus, rainfall of only 17.4 mm was considered as effective precipitation for further calculations purpose. Average sunshine remained

considerably lower as compared to normal data. Total evaporation remained lower compared to normal data during the period under consideration.

2012-13: During the 2012-13 potato growing period [Fig. 2: (a) to (d)], the average temperature did not vary significantly except during Ist and IInd week of January when it was comparatively lower than the normal data. Total rainfall was not uniformly distributed and was lower than the normal range. There were two events of effective rainfall measuring 17.4 mm and 8.2 mm of water in the IIIrd week of December and January, respectively. But the second event of rainfall occurred after dehauling of potato vines. Thus, only 17.4 mm of rainfall was considered for further calculation purpose. Average humidity and average sunshine hrs followed the trend of previous year although the sunshine hours showed less divergence from normal as compared to previous year. The average sunshine hours were comparatively higher than the previous year.

3. Results and Discussion

3.1 Analysis of variance

The analysis of variance indicated that years significantly affected all the variables except plant height and above ground dry matter accumulation both at 30 DAP (Table 2). According to the data pooled over two years, irrigation treatments significantly affected all variables except plant height and above ground dry matter accumulation both at 30 DAP and graded tuber yield (large, medium, small and smaller size tubers). Differences between irrigation treatments in 2011, and 2012 and “year $\times$ treatment” interactions were significant at 5% level of probability for WUE, WUEi, marketable tuber yield, average tuber weight, tuber dry weight, root dry weight, source to sink ratio, leaf are index, and plant height and above ground dry matter accumulation both at 60 DAP and at harvest. These interactions, statistically significant for the measured parameters, indicated that irrigation treatments responded variably to different years.

3.2 Irrigation water application and soil water tension dynamics

The number and amount of irrigation for different treatments during the potato growing seasons are shown in Table 3. The depth of water for each irrigation event of treatments was constantly changing during the growing season from 45 to 46 mm, the corresponding change was from 57.5 to 60 mm for control. Although higher initial amount of irrigation was received by the control than other treatments. The initial irrigation to all the treatments was assumed to be same as the soil moisture storage at the time of complete emergence of tubers was found uniform (data not shown). The targeted values of tensiometer recording were started at uniform moisture storage in all the treatments. The number of irrigations varied from 1 to 7 during both of the planting seasons. The irrigation amount received after complete crop emergence by S₂₀D₂₀, S₃₅D₂₀, S₅₀D₂₀, S₂₀D₃₀, S₃₅D₃₀, S₅₀D₃₀, S₂₀D₄₀, S₃₅D₄₀, S₅₀D₄₀, control

treatment plots were 227.5, 182.0, 135.0, 180.0, 135.0, 90.0, 180.0, 90.0, 45.5 and 420 mm in 2011, and 225.0, 135.0, 90.0, 181.6, 90.0, 45.0, 136.5, 92.0, 45.0 and 402.5 mm in 2012, respectively. One major event of effective rainfall during the active growth of crop (December, 2012) disturbed the targeted potentials on the corresponding days, thus less irrigation water was supplied to $S_{35}D_{20}$, $S_{50}D_{20}$, $S_{35}D_{30}$, $S_{50}D_{30}$, and $S_{20}D_{40}$ treatments during 2012. This event might have increased soil moisture resulting in increased SMP in these treatment plots. Other small rains and untimely rains had little effect on irrigation water supplied to treatments. As expected, treatment $S_{50}D_{40}$ received least amount of water during both the years due to lower SMP. Our results are consistent with the findings of Wang et al. (2011), they also reported application of lower amount of irrigation water at lower SMP. The control had received highest amount of irrigation water.

Since sufficient amount of irrigation water was applied for rooting and establishment of crop to all the treatments (para 2.4.), thus the initial values of SWT after complete plant emergence were close to 12 to 14 kPa for all the treatments during both the years (Fig. 3). Depending upon the treatment, the values of SWT fluctuated in variable range during the cropping period. The soil water tensions for the treatments $S_{50}D_{20}$, $S_{50}D_{30}$ and $S_{50}D_{40}$ showed larger variations compared to the other SWT treatments owing to higher SWT values at different soil depths. These treatments fell to nearly 10 kPa second day after irrigation and often exceeded slightly to their fixed value before irrigation. However, the thresholds for treatments $S_{20}D_{20}$, $S_{20}D_{30}$ and $S_{20}D_{40}$ were often slightly surpassed and were comparatively difficult to maintain due to lower SWT values in the upper soil. The possible reason may be time gap between water application and the recovery of soil water tension. The other reason may be higher hydraulic conductivity at higher soil matric potential. Although temporal and spatial distribution of SMP was not measured in our study, but it is assumed that there was lower soil moisture in the effective root zone area.

3.3. Water use efficiency (WUE) and Irrigation water use efficiency (WUE_i)

Treatments $S_{50}D_{40}$ and $S_{50}D_{30}$ increased 186% and 183% water use efficiency, with a concomitant water saving of 70% and 62 % than that of control during the year 2011 (Table 3). During the year 2012, $S_{50}D_{30}$ increased WUE by 218%, with a water saving of 69% followed by $S_{50}D_{20}$ with corresponding values of 186% and 61%. The check treatment (control) recorded lowest WUE as this treatment had received highest amount of water volume i.e. 5474 and 5299 m³ ha⁻¹ during first and second year. The WUE in $S_{35}D_{20}$ was upto 159% higher than control when data was pooled over two years. The analysis of pooled data further revealed that WUE followed the order of $S_{50}D_{30} > S_{50}D_{20} > S_{50}D_{40} > S_{35}D_{20} > S_{35}D_{30} > S_{35}D_{40} > S_{20}D_{40} > S_{20}D_{30} > S_{20}D_{20} > \text{control}$. The first six treatments in the order were statistically at par and the next three were again statistically at par with each other. Similar

trends of higher water use efficiency with the use of lower volume of water were also obtained by Xie et al. (2012) in China. Zhao et al. (2014) computed the WUE ($\text{kg ha}^{-1}\text{mm}^{-1}$) based on the dry tuber yield and Ahmadi et al. (2014) divided the total tuber fresh weight (kg) by the total applied water (m^3) to calculate water productivity.

The similar trends as for WUE were recorded for WUE_i . Treatments $\text{S}_{50}\text{D}_{30}$ and $\text{S}_{50}\text{D}_{40}$ recorded maximal WUE_i followed by $\text{S}_{35}\text{D}_{20}$ in 2011. In the year 2012, $\text{S}_{50}\text{D}_{30}$ recorded highest WUE_i followed by $\text{S}_{50}\text{D}_{20}$ and $\text{S}_{35}\text{D}_{20}$. Similar to WUE, lowest values of WUE_i were recorded in the control during both the years. $\text{S}_{35}\text{D}_{20}$ recorded 105 and 147% higher WUE_i than that of control treatment in 2011 and 2012, respectively. The WUE_i ranged from 34.9 to 78.1 in 2011 and 37.2 to 106.4 in 2012. The analysis of pooled data followed the trends of second year. Approximately similar range of WUE was obtained by Wang et al. (2011) except for the lowest value obtained in our experiment for the control treatment. The values of WUE obtained by Kang et al. (2004) was higher than values of WUE_i obtained in our investigation which may be due to less irrigation water consumption under drip irrigation system. While, the WUE (30.2 to $58.4 \text{ kg ha}^{-1}\text{mm}^{-1}$) obtained by Panigrahi et al. (2001) was lower than WUE_i in our experiment because the tuber yield obtained by them was lower than that of ours.

3.4. Marketable tuber yield and average tuber weight

Treatment $\text{S}_{20}\text{D}_{20}$ produced 12 % higher marketable tuber yield in 2011 and 9% in the year 2012 than that of control which was statistically at par with $\text{S}_{35}\text{D}_{20}$ during both the years (Table 4). Both of these treatments were targeted at lower soil water suction measured in the upper soil layer as compared to the other treatments. The pooled analysis of data also showed the same results, which were more similar to the second year results. The tuber yield for control treatment followed the two best treatments in terms of marketable tuber yield. This was in fact reasonable because this treatment had inadvertently received the most of irrigation water. The lowest marketable tuber yield *ca.* 83% and 90% lower than $\text{S}_{20}\text{D}_{20}$ in 2011 and 2012, respectively was recorded for $\text{S}_{50}\text{D}_{40}$. In this treatment, lowest SMP was measured at 0.4 m soil depth and it had received lowest amount of water volume during both the years. The tuber growth was restrained in $\text{S}_{50}\text{D}_{40}$ which may probably due to soil moisture deficit in the vicinity of root zone. Our result is consistent with the findings of Wang et al. (2007). Kang et al. (2004) also found that there was continuous decrease in the tuber yield as the soil matric potential increased from -25 kPa to -55 kPa. However, the differences between $\text{S}_{50}\text{D}_{20}$ and $\text{S}_{20}\text{D}_{40}$, $\text{S}_{35}\text{D}_{30}$, control and $\text{S}_{20}\text{D}_{30}$ and $\text{S}_{50}\text{D}_{30}$ and $\text{S}_{35}\text{D}_{40}$ treatments were not significant during both the years. There was decline in the potato yield with drop in SMP from -20 kPa to -50 kPa at all the installation depths of tensiometer (Duncan's test, $P < 0.05$). This decline was

18% and 21% at installation depth of 20 cm, 26% and 24% at 30 cm and 57.7% and 58 % at 40 cm soil depth in 2011 and 2012, respectively.

The relationship between the average marketable tuber yield (avg. mkt y) and total irrigation water applied (sum of Irrigation water and precipitation = iwp) for different treatments (Fig. 4) is given by the equation

$$\text{Avg. mkt y} = 0.187 \text{ iwp} + 122.6$$

Where, Avg. mkt y is measured in quintal per hectare and total irrigation water in mm. The coefficient of determination or determination factor (R^2) between these two variables was found to be 0.418. The marketable tuber yield seemed to increase with increase in irrigation water application.

The relationship between the marketable tuber yield and water use efficiency is shown in Fig. 5. In general, the higher values of water use efficiency correspond to lower marketable tuber yield and *vice versa*. Consistently higher marketable tuber yield and about double the water use efficiency in $S_{35}D_{20}$ and $S_{20}D_{20}$ was recorded as compared to the control plot over the two years. Our results suggest that lower SMP of -35 kPa maintained at soil depth of 20 cm, enhance WUE and maintain tuber yield with medium saving of irrigation water and these effects would be associated to improved osmotic adjustment for better growth and crop development.

In terms of average tuber weight, highest average tuber weight was recorded for control (51.1g and 54.2 g for 2011 and 2012) which was followed by $S_{20}D_{20}$, $S_{35}D_{20}$, $S_{20}D_{30}$, $S_{20}D_{40}$ and $S_{50}D_{20}$ treatments during both the years. The similar results were obtained when further analysis for pooled data was conducted. These treatments were statistically at par with each other. The highest tuber weight in the control treatment was probably on account of sufficient moisture in the root zone which may have resulted in better growth of tubers resulting in large sized tubers. Wang et al. (2007) also reported higher marketable tuber weight under higher SMP of -25 kPa than that under -45 and -55 kPa. The tuber growth in the treatments $S_{50}D_{40}$ and $S_{35}D_{40}$ was restrained as these treatments might had undergone water stress to some extent due to declined SMP in the active root growing area.

3.5. Quality Tuber Production

General order of graded tuber yield obtained was smaller > small > medium > large sized tubers irrespective of the treatments during both the years (Table 5). The similar trend to ours for graded tuber yield was recorded by Bisht et al. (2012) in the North Indian plains. Significantly higher large size tuber yield was recorded for $S_{20}D_{20}$ and $S_{20}D_{20}$ & $S_{35}D_{20}$ (30.1 q/ha in 2011 and 33.4 & 31.5 q/ha in 2012 respectively), which was followed by $S_{35}D_{20}$, control, $S_{20}D_{30}$, $S_{50}D_{20}$ during 2011 and control, $S_{20}D_{40}$, $S_{50}D_{20}$, $S_{20}D_{30}$ treatments during the

year 2012. Further, analysis of pooled data showed that only two treatments $S_{20}D_{20}$, $S_{35}D_{20}$ were statistically at par with control and all other treatments were lower than these treatments. Treatments $S_{35}D_{20}$ during 2011 and $S_{20}D_{20}$ during the year 2012 produced highest medium size tuber yield. The treatments, $S_{20}D_{20}$, control and $S_{20}D_{30}$ in the year 2011 and treatments, $S_{35}D_{20}$, control, and $S_{20}D_{30}$ followed these treatments in 2012. However, when further analysis for pooled data was conducted both $S_{20}D_{20}$ and $S_{35}D_{20}$ were significantly higher than all other treatments and at par with each other. Highest quantity of large and medium size tuber yield for these two treatments might be due to higher overall growth and development of plants owing to higher soil matric potential. Noticeably higher quantity of large size tubers in control treatment albeit its highest overall per cent of discarded tubers was due to sufficient soil moisture in the root zone owing to higher quantity of irrigation water received by this treatment. Small size tuber yield followed the order of $S_{20}D_{20} > S_{35}D_{20} > S_{20}D_{30}$ during both the years. The analysis of pooled data for small size tuber yield showed that these treatments were significantly higher and statistically at par with each other. Smaller size tuber yield followed the order of $S_{20}D_{20} > S_{35}D_{20} > S_{20}D_{30} > S_{20}D_{40} \sim \text{control}$ in 2011 and $S_{20}D_{20} > S_{35}D_{20} > \text{control} > S_{20}D_{30} > S_{20}D_{40} > S_{50}D_{20} > S_{35}D_{30}$ in 2012 years. However, treatment $S_{50}D_{40}$ recorded lowest tuber yield for all the four selected grades i.e. large, medium, small and smaller size tubers during both the years which may probably because lower soil moisture content in the root zone area during crop growth and development period. Similarly, Cantore et al. (2014) recorded maximum percent of undersized tubers in the rainfed treatment.

The green percent of tubers was significantly higher under $S_{50}D_{40}$ during both the years. However treatment $S_{35}D_{30}$ also produced higher green tubers during first year. Further analysis of pooled data showed that both of these treatments produced highest percent of green tubers. Lowest green per cent of tubers was recorded for $S_{35}D_{20}$ during both the years. Greening of tubers is related with direct exposure of growing tubers to sunlight. Dry soil surface may easily expose tubers to direct sunlight and it may probably be possible that the surface soil of treatments $S_{50}D_{40}$ and $S_{35}D_{30}$ was drier for higher times. Significantly higher blemished per cent of tubers was recorded in control during both the years. All other treatments recorded statistically lower blemished per cent of tubers. Significantly lower blemished per cent of tubers was recorded in $S_{20}D_{20}$ during 2011 as well as when the data was pooled over two years. Similar tendency to blemished percent of tubers was also found for discarded tuber percent. Both treatments $S_{20}D_{20}$ and $S_{35}D_{20}$ recorded significantly lower discarded percent of tubers as shown by the analysis of pooled data. The highest discarded tuber percent was recorded under control treatment during both the years which may be due to

higher amount of water application in this treatment leading to excessive soil moisture and augmented tuber deterioration. Qasim et al. (2013) also reported higher green and injured percent of tubers under farmer's practice. Treatment S₅₀D₄₀ followed control during both the years which may be due to moisture deficit in the root zone as this treatment received minimum irrigation water during both the years. Thus, both low and high moisture may affect tuber quality. Lowest green and blemished percent of tubers was recorded under S₃₅D₂₀, our results are consistent with the findings of Qin et al. (2014). They reported lowest percent of green and blemished tubers under ridge planting in completely mulched wide ridges alternated with narrow ridges under low fertility area at Dingxi, Northwest China. In our experiment also tubers were planted in the ridges in the low fertility area and treatment S₃₅D₂₀ might had received optimum soil moisture conditions for growth and development of tubers.

3.6. Tuber dry weight, Dry tuber yield, Root dry weight and Source to sink ratio

The highest tuber dry weight (per 100g of fresh weight) was recorded for S₅₀D₄₀ during both the years. Treatments S₃₅D₄₀ and S₅₀D₃₀ followed S₅₀D₄₀ during both the years (Table 6). When further analysis of pooled data was conducted it was found that treatments S₅₀D₂₀, S₃₅D₃₀, S₅₀D₃₀, and S₅₀D₄₀ were statistically at par with each other. Treatment control recorded minimum tuber dry weight during both the years which may probably be due to higher per cent of water present in the tubers under this treatment as compared to other treatments. On the contrary highest tuber dry weight in S₅₀D₄₀ indicated presence of lower quantity of water in the tubers. Dry tuber yield was derived from the multiple of tuber dry weight and marketable tuber yield. The treatments S₃₅D₂₀, S₂₀D₂₀, S₂₀D₃₀ and S₅₀D₂₀ increased dry tuber yield by 34%, 28%, 24%, and 22% in 2011, and 28%, 20%, 13%, and 12% in 2012, respectively as compared to the control treatment. The tuber dry weight reported by us is higher than the previous studies (Singh et al. 2011) conducted in the region. The reason for obtaining higher tuber dry weight may be the error during the estimation or some other unknown cause.

The highest root dry weight per plant was recorded for control which was statistically at par with S₂₀D₂₀ and S₃₅D₂₀ treatments (Table 6). The higher amount of water volume received by control, S₂₀D₂₀ and S₃₅D₂₀ treatments may probably have resulted in the well developed root system (Table 3). The treatment S₅₀D₄₀ recorded lowest root dry weight during both the years as it received lowest amount of water volume during both the years. It was reported by Wang et al. (2007) that the root weight density declined as the SMP decreased from -35 to -55 kPa. However, similar root dry weight among full, deficit, and partial root-zone drying irrigation treatments was recorded by Ahmadi et al. (2010). Lowest

source to sink ratio was recorded for $S_{35}D_{40}$, $S_{35}D_{30}$ and $S_{50}D_{30}$ & for $S_{50}D_{30}$ and $S_{35}D_{30}$ which were statistically at par during 2011 & 2012, respectively. The analysis of pooled data also showed that treatments $S_{50}D_{30}$, $S_{35}D_{30}$, and $S_{35}D_{40}$ were significantly lower among all other treatments and statistically at par with each other. Source to sink ratio signifies the translocation efficiency of assimilates from leaves to the tubers and the lowest value indicated the highest translocation of assimilates to the tubers. However, significantly higher source to sink ratio obtained under control signifies the poor translocation efficiency of assimilates to the tubers. It was observed in general that the treatments which had received lower amount of water volume showed lower values of source to sink ratio as compared to the treatments receiving higher amount of water volume. It may be due to higher translocation efficiency of assimilates to tubers at lower soil moisture content in the root zone. Our results obtained for source to sink ratio showed that this parameter was not as good indicator of crop growth as others. These results obtained for source to sink ratio are contrary to the findings by Ierna and Mauromicale (2012), who had reported lower values of source to sink ratio for the treatments which had received higher amount of water volume. While, non significant differences among different treatments were recorded by Cantore et al. (2014) for source to sink ratio.

The higher values of root dry weight per plant and dry tuber yield (kg ha^{-1}) recorded for $S_{20}D_{20}$ and $S_{35}D_{20}$ treatments, point out the need for keeping the top soil (20 cm) moist by maintaining lower SWT. Both of these treatments might had maintained optimum soil moisture in the root zone area for proper root development and higher nutrient uptake resulting in higher marketable tuber yield and thus higher dry tuber yield. Treatment $S_{20}D_{30}$, which followed the above said treatments for these two assessed variables indicates maintaining lower SWT (20 kPa) in top 30 cm soil depth. Although the root length density was not studied by us, but the inferences from the results may be drawn that major root mass was confined to 30 cm soil depth.

3.7. Growth parameters

Plant height at 30 DAP was not affected significantly under different treatments, but it varied when recorded on 60 and 90 DAP under different treatments (Fig. 6). Almost similar values of plant height at 30 DAP were recorded for all the treatments during both 2011 and 2012 years, although the plant height during the 2012 was higher as compared to the 2011. Non-significant differences among the treatments 30 DAP during both the years may be due to approximately similar amount of irrigation water received by all the treatment plots during early growing period. However, slightly higher plant height was recorded for $S_{20}D_{20}$ during both the years which may be due to higher soil moisture as this treatment received irrigation

on 23rd and 27th day after planting during first and second year. Plant height at the 60 DAP and at harvest during 2011, was significantly higher for control followed by S₂₀D₂₀, S₃₅D₂₀ and S₂₀D₃₀ treatments, as compared to all other treatments (Fig. 6). While, during 2012 significantly higher plant height after 60 DAP and at the time of harvest was recorded for S₂₀D₂₀ which was followed by S₃₅D₂₀, control and S₂₀D₃₀ treatments. The control treatment had received highest amount of irrigation water but smaller plant height was recorded for control in 2012 that may be due to higher secondary branches developed by the plants which are evident from the higher above ground dry weight accumulation under control in the same year (mentioned in the next para). When further analysis of pooled data was conducted it was shown that S₂₀D₂₀ and control at 60 DAP and S₂₀D₂₀, S₃₅D₂₀ and control at the time of harvest were statistically similar. During both the years lowest plant growth was recorded for S₅₀D₄₀ at 60 DAP and at the time of harvest. The plant growth was restrained by soil water deficit in this treatment. Both of S₂₀D₂₀ and S₃₅D₂₀ treatments received irrigation at lowest SWT as compared to all other treatments which might have caused higher plant growth during active growth periods. Higher plant growth at lower SMP was also reported by Wang et al. (2011).

The tendency of leaf area index (LAI) was same as for plant height at 60 DAP and at the time of harvest. Highest LAI was recorded in control (3.41 & 3.67 during 2011 & 2012) which was statistically at par with S₂₀D₂₀ (3.15 & 3.50 during 2011 & 2012) and S₃₅D₂₀ (2.83 & 3.23 during 2011 & 2012) treatments followed by S₂₀D₃₀ (2.68 & 2.97 during 2011 & 2012) treatment (Fig. 7). However, when pooled analysis was conducted it was shown that only treatments S₂₀D₂₀ and control were significantly higher among all other treatments. The control treatment showed expanded LAI due to higher water application. Higher LAI for above mentioned treatments indicated increased formation of photosynthates owing to higher interception of radiation. It is evident from the assessed variables for growth and yield that these treatments had formation of higher photosynthates resulting in translocation of higher quantity of assimilate towards the tubers. Zhao et al. (2014) also reported increase in LAI with the increase in plant height.

In case of above ground dry matter accumulation 30 DAP, all the treatments during both the years had non-significant differences which may be due to uniform growth in all the treatment plots during early growing period. However, when further analysis of pooled data was conducted it was shown that treatment S₂₀D₂₀ was significantly higher and statistically at par with S₃₅D₂₀ among all the treatments. It may probably be due to early crop emergence and higher plant height at this stage for these treatments. At 60 DAP, significantly higher above ground dry matter accumulation (DMA) was recorded for control (13.1 g per plant), S₂₀D₂₀

(12.7 g per plant), S₃₅D₂₀ (12.4 g per plant), S₂₀D₃₀ (12.2 g per plant) and S₂₀D₄₀ (12.1 g per plant) as compared to all other treatments during the year 2011(Fig. 8). Nearly similar trend was recorded during the year 2012. Significantly higher above ground DMA at harvest was recorded both during 2011 and 2012 for control (16.5 and 17.1 g per plant), S₂₀D₂₀ (15.9 and 16.5 g per plant) and S₃₅D₂₀ (15.3 and 15.8 g per plant) followed by S₂₀D₃₀ (13.9 and 13.7 g per plant) and S₂₀D₄₀ (13.2 and 13.1 g per plant) treatments. Lowest above ground DMA was recorded for S₅₀D₄₀ at 60 DAP and at the time of harvest during both the years. The analysis of pooled data showed more similarities with the second year results both during 60 DAP and at the time of harvest. Treatments S₂₀D₂₀ and S₃₅D₂₀ recorded 66 % and 59 % higher DMA at harvest as compared to S₅₀D₄₀ during 2011 and these figures were 57 % and 50 %, respectively for the year 2012. The lowest above ground dry matter accumulation under S₅₀D₄₀ might be due to lower soil moisture in the root zone as a result of combination of higher SWT (50 kPa) at more soil depth (40 cm). Higher plant height and above ground DMA was recorded for S₂₀D₂₀, S₃₅D₂₀ and control, as indicated by higher plant growth and development for these treatments. Qin et al. (2014) also reported that higher dry matter accumulation is an indicator of higher plant growth.

The results obtained in the experiment, brings out the importance of maintaining higher SMP in upper soil layer for S₂₀D₂₀ and S₃₅D₂₀ (-20 kPa and -35 kPa at 20cm soil depth) treatments which gave higher plant height, above ground dry matter accumulation, leaf area index, higher quantity of good quality graded tuber yield, average tuber weight, marketable tuber yield. These treatments were followed by S₂₀D₃₀ treatment which belonged to SMP of -20 kPa at 30 cm soil depth for all the above mentioned variables.

Nevertheless, the WUE was lower for S₃₅D₂₀ during first year but it helped in better growth and development of the crop. It registered more than double WUE than traditional practice of the area (control).The WUE averaged over two years for S₃₅D₂₀ ranked 4th after S₅₀D₃₀, S₅₀D₂₀ and S₅₀D₄₀ treatments. So based on higher value of WUE, treatment S₃₅D₂₀ qualifies to be the best treatment. This treatment showed edge over other treatments in terms of plant growth, development, tuber quality and yield in addition to the medium saving of irrigation water. Highest saving of 70% irrigation water was recorded in the S₅₀D₄₀ treatment followed by S₅₀D₃₀ (66%) as compared to traditional irrigation practice. But, plant growth and ultimately the tuber size and tuber yield were drastically reduced in the S₅₀D₄₀ and S₅₀D₃₀ treatments due to continuous soil moisture deficit in the present investigation. The S₃₅D₂₀ treatment which registered higher WUE, utilized 49% less irrigation water as compared to the traditional irrigation practice in the region. This might be explained that irrigation schedule of

this treatment created optimum soil environmental conditions for tuber and root growth, favouring better water and nutrient uptake. Apparently two reasons may be put forward in the support of keeping lower soil moisture tension of 35 kPa in the upper 20 cm soil layer. The first reason may be the short life cycle of potato crop (in our case it was 90 days for dehauling and additional 15 days for tuber uprooting) leading to early bulking of crop requiring ready availability of moisture which is essential for maintaining turgidity of leaves and tuber formation and enlargement. Secondly, the potato plant has shallow and sparse root system and about 85% of root mass is confined to the upper 30 cm soil depth (Opena and Porter, 1999, Iwama, 2008). It seems that the dense layer of root mass in the upper soil layer absorbed most of water without allowing it to percolate to the deeper soil layers utilizing it for better nutrient absorption and overall plant growth. When the irrigation was given for maintaining proper soil moisture at soil depth of 40 cm, the presence of lower soil moisture in the top soil layer may have resulted in poor plant growth and lower tuber yield. The better hydraulic conductivity of soil may have allowed the water to percolate down in the deeper layers of soil without its proper use by the roots of potato plant (Table 1). Delayed irrigation at higher SWT ($S_{50}D_{20}$, $S_{50}D_{30}$, $S_{50}D_{40}$) may had caused lower soil moisture content in the root zone which may had resulted in reduced transpiration and closure of stomata on account of high diffusion pressure deficit in the leaves. Although the evapotranspiration was not studied in the present investigation but higher SWT decline the SMP of the soil thus affecting evapotranspiration of the plants. Light irrigations for maintaining lower soil moisture tension in upper soil layer ($S_{35}D_{20}$) was better than the frequent and heavier irrigations as practised by the farmers which lead to higher discarded production and reduced WUE.

The analysis of growth and yield parameters showed that plant height, LAI, above ground dry matter accumulation, tuber size, tuber dry weight, root dry weight and graded and marketable tuber yield (Fig. 9) was on higher side during the year 2012 as compared to the year 2011. Variation in yield in the consecutive years for same crop cultivar has also been reported by Ferreira and Goncalves (2007) and Shahnazari et al. (2008). In our study, the difference may be attributed to better sunshine hrs during the planting year of 2012. The sunshine hours were reduced to zero during higher number of days in November, December, 2011 and January, 2012 as compared to the planting season of 2012-13.

4. Conclusions: Irrigation scheduling based on the soil water tension is successful provided the SWT is carefully recorded and irrigation is applied immediately to reduce the experimental error. Our results indicated that the lower soil moisture tension of 35 kPa in the upper 20 cm soil layer ($S_{35}D_{20}$) has resulted in the increased root biomass showed by higher

root dry weight, which had improved above ground biomass as well as tuber growth and development. This treatment recorded higher marketable tuber yield, WUE and WUEi in addition to the saving of medium irrigation water among all other treatments tested. Adopting this threshold corresponds to 3 to 4 irrigations of 45 to 45.5 mm each depending on the rainfall during potato growing period. Two separate irrigations of 50 mm each were applied, first as pre-irrigation and second irrigation to substantiate emergence. Thus, application of single irrigation two weeks after the complete emergence of crop and remaining 2-3 irrigations at 17 days interval may save 49% irrigation water as compared to the traditional irrigation practice. The soil moisture deficit in the top soil layer at higher soil moisture tension of 50 kPa had resulted in poor crop growth and development. Soil moisture tension of 50 kPa under higher soil depth of 40 cm showed the highest reduction in the crop growth and tuber yield implying water stress conditions. Traditional irrigation practice had received higher quantity of water resulting in tuber health deterioration due to more than optimum soil moisture in the root zone. There may be redundancy in soil water which may probably have reduced water and nutrient uptake owing to decreased soil aeration in this treatment, although such effects were not visible.

Rain patterns and meteorological conditions of the area can also influence the desired threshold of soil matric potential which ultimately may affect the experimental results as the researchers seek to find the optimum threshold soil matric potential for use in scheduling irrigation to potato. It is known that tuber initiation and tuber bulking are more sensitive to soil moisture stress as compared to the other growing stages of the crop. Thus varying the soil water tension with the potato developmental stages may save higher water without reducing tuber quality and yield. Further, there is need for standardizing soil water tension for irrigation scheduling to potato under various water saving irrigation methods including deficit irrigation practices in the region.

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Table 1: Physical characteristics of soil before planting potato in the year 2011 and 2012.

Soil depth (cm)	Bulk density (g cm ⁻³)		Saturated conductivity (cm hr ⁻¹)		Unsaturated conductivity (cm hr ⁻¹)				Infiltration rate (cm hr ⁻¹)	
					Suction I (2cm)		Suction II (4cm)			
Year	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
0-15	1.40	1.37	305.0	310.0	103.0	104.0	33.5	33.0	6.93	7.03
15-30	1.55	1.51	136.0	140.0	27.0	28.0	11.0	10.0		
30-45	1.60	1.65	143.0	144.0	15.5	14.0	14.0	13.0		
45-60	1.64	1.72	113.0	115.0	25.0	23.0	24.0	22.5		

Table 2: Results of variance analysis of WUE, WUEi, marketable tuber yield, average tuber weight, graded tuber yield (large, medium, small, smaller), green, blemished and discarded percent, tuber dry weight, root dry weight, source to sink ratio, plant height (30, 60DAP, at harvest) above ground dry matter accumulation (30, 60DAP, at harvest) of potato crop under different irrigation treatments for 2011, 2012 plantings and combined years (pooled).

Source	d.f. ^a	Significance of F-ratios												
		<u>Water use efficiency</u>			<u>Irrigation water use efficiency</u>			<u>Marketable tuber yield</u>			<u>Average tuber weight</u>			
	1	2	2011	2012	2-year	2011	2012	2-year	2011	2012	2-year	2011	2012	2-year
Years (Y)	-	1			*			*			*			*
Blocks	2	2	ns ^b	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Treatments (T)	9	9	*	*	*	*	*	*	*	*	*	*	*	*
Y×T	-	9			*			*			*			*
Error	18	36												
Source	d.f.	Significance of F-ratios												
	1	2	<u>Large size tuber yield</u>			<u>Medium size tuber yield</u>			<u>Small size tuber yield</u>			<u>Smaller size tuber yield</u>		
	1	2	2011	2012	2-year	2011	2012	2-year	2011	2012	2-year	2011	2012	2-year
Years (Y)	-	1			*			*			*			*
Blocks	2	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Treatments (T)	9	9	*	*	*	*	*	*	*	*	*	*	*	*
Y×T	-	9			ns			ns			ns			ns
Error	18	36												
Source	d.f.	Significance of F-ratios												
	1	2	<u>Green percent</u>			<u>Blemished percent</u>			<u>Discarded percent</u>			<u>Tuber dry weight</u>		
	1	2	2011	2012	2-year	2011	2012	2-year	2011	2012	2-year	2011	2012	2-year
Years (Y)	-	1			*			*			*			*
Blocks	2	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Treatments (T)	9	9	*	*	*	*	*	*	*	*	*	*	*	*
Y×T	-	9			*			*			*			*
Error	18	36												

Source	d.f.		Significance of F-ratios											
			<u>Root dry weight</u>			<u>Source to sink ratio</u>			<u>Plant height (30DAP)</u>			<u>Plant height (60DAP)</u>		
	1	2	2011	2012	2-year	2011	2012	2-year	2011	2012	2-year	2011	2012	2-year
Years (Y)	-	1			*			*			ns			*
Blocks	2	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Treatments (T)	9	9	*	*	*	*	*	*	ns	ns	ns	*	*	*
Y×T	-	9			*			*			ns			*
Error	18	36												
Source	d.f.		Significance of F-ratios											
			<u>Plant height (at harvest)</u>			<u>Above ground DMA (30DAP)</u>			<u>Above ground DMA (60DAP)</u>			<u>Above ground DMA (at harvest)</u>		
	1	2	2011	2012	2-year	2011	2012	2-year	2011	2012	2-year	2011	2012	2-year
Years (Y)	-	1			*			ns			*			*
Blocks	2	2	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Treatments (T)	9	9	*	*	*	ns	ns	ns	*	*	*	*	*	*
Y×T	-	9			*			ns			*			*
Error	18	36												
Source	d.f.		Significance of F-ratios											
			<u>Leaf area index</u>											
	1	2	2011	2012	2-year									
Years (Y)	-	1			*									
Blocks	2	2	ns	ns	ns									
Treatments (T)	9	9	*	*	*									
Y×T	-	9			*									
Error	18	36												

a Degrees of freedom for individual year (1) and combined (2) over two years.

b Non-significant

* Significant at the 5% of probability level (<0.05)

Table 3: Number of irrigations, average water application per irrigation, seasonal total irrigation depth, total water application ($\text{m}^3 \text{ha}^{-1}$) and water use efficiency (kg tuber dry weight m^{-3} of water applied) for different treatments during 2011 and 2012 plantings.

Treatments	Pre-plant irrigation + Crop establishing irrigation	Number of irrigations		Average irrigation application (mm)		Seasonal irrigation application (mm)		Water volume ($\text{m}^3 \text{ha}^{-1}$) (seasonal irrigation application + total rainfall)			WUE (kg tuber dry weight m^{-3} of water volume)			WUE _i (kg $\text{ha}^{-1} \text{mm}^{-1}$)		
Year	2011 & 2012	2011	2012	2011	2012	2011	2012	2011	2012	Average	2011	2012	Pooled	2011	2012	Pooled
S ₂₀ D ₂₀	50 mm +50 mm	5	5	45.5	45.0	227.5	225.0	3449	3424	3436.5	0.94d	1.04f	0.99c	63.4d	68.0d	65.7f
S ₃₅ D ₂₀	50 mm +50 mm	4	3	45.5	45.0	182.0	135.0	2994	2524	2759.0	1.14abc	1.49bc	1.32abc	71.7abc	91.8b	81.8bc
S ₅₀ D ₂₀	50 mm +50 mm	3	2	45.0	45.0	135.0	90.0	2524	2074	2299.0	1.23ab	1.60b	1.42ab	74.7ab	96.1b	85.4b
S ₂₀ D ₃₀	50 mm +50 mm	4	4	45.0	45.4	180.0	181.6	2974	2990	2982.0	1.06bcd	1.12ef	1.09bc	66.9cd	67.9d	67.4f
S ₃₅ D ₃₀	50 mm +50 mm	3	2	45.0	45.0	135.0	90.0	2524	2074	2299.0	1.14abc	1.48bc	1.31abc	69.5bcd	88.4b	78.9cd
S ₅₀ D ₃₀	50 mm +50 mm	2	1	45.0	45.0	90.0	45.0	2074	1624	1849.0	1.30a	1.78a	1.54a	78.1a	106.4a	92.2a
S ₂₀ D ₄₀	50 mm +50 mm	4	3	45.0	45.5	180.0	136.5	2974	2539	2756.5	1.03cd	1.28de	1.15bc	63.9d	77.9c	70.9ef
S ₃₅ D ₄₀	50 mm +50 mm	2	2	45.0	46.0	90.0	92.0	2074	2094	2084.0	1.23ab	1.28de	1.25abc	73.8ab	74.3cd	74.0de
S ₅₀ D ₄₀	50 mm +50 mm	1	1	45.5	45.0	45.5	45.0	1629	1624	1626.5	1.32a	1.39cd	1.36ab	78.0a	80.3c	79.1cd
Control	0 +110 mm	7	7	60.0	57.5	420.0	402.5	5474	5299	5386.5	0.46e	0.56g	0.51d	34.9e	37.2e	36.1g
p-value	-	-	-	-	-	-	-	-	-	-	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Column mean with different letters differ significantly at p-value <0.05. ** The effective total rainfall during both the planting seasons was 17.4mm.

Table 4: Average tuber weight (g) and marketable tuber yield (q ha⁻¹) for different treatments for potato plantings in the year 2011 and 2012.

Treatment	Average tuber weight (g)			Marketable tuber yield (q ha⁻¹)		
Year	2011	2012	Pooled	2011	2012	Pooled
S ₂₀ D ₂₀	50.6a	53.2a	51.9ab	207.5a	220.9a	214.2a
S ₃₅ D ₂₀	49.9a	51.8ab	50.9abc	202.3ab	215.7ab	209.0ab
S ₅₀ D ₂₀	44.8ab	45.1abc	45.0cde	175.5cd	182.5de	179.0cd
S ₂₀ D ₃₀	46.7ab	47.2abc	47.0abcd	187.4bc	191.1cd	189.3c
S ₃₅ D ₃₀	43.5ab	43.1bcd	43.3de	163.3d	167.9ef	165.6de
S ₅₀ D ₃₀	40.6bc	40.4cd	40.5de	148.4e	154.2fg	151.3ef
S ₂₀ D ₄₀	45.5ab	46.4abc	46.0bcd	178.8cd	184.1d	181.5cd
S ₃₅ D ₄₀	39.8bc	38.5cd	39.2ef	140.2e	142.6g	141.4f
S ₅₀ D ₄₀	33.8c	33.5d	33.7f	113.4f	116.5h	115.0g
Control	51.1a	54.2a	52.7a	185.1c	203.1bc	194.1bc
p-value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Column mean with different letters differ significantly at p-value <0.05.

Table 5: Graded tuber yield (q ha⁻¹) and discarded tuber (%).

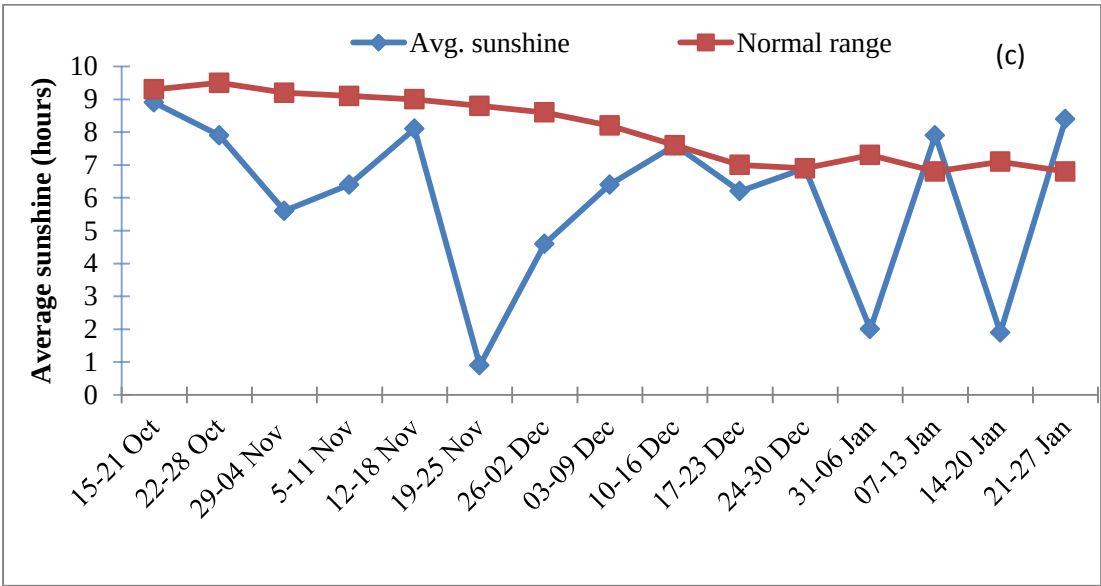
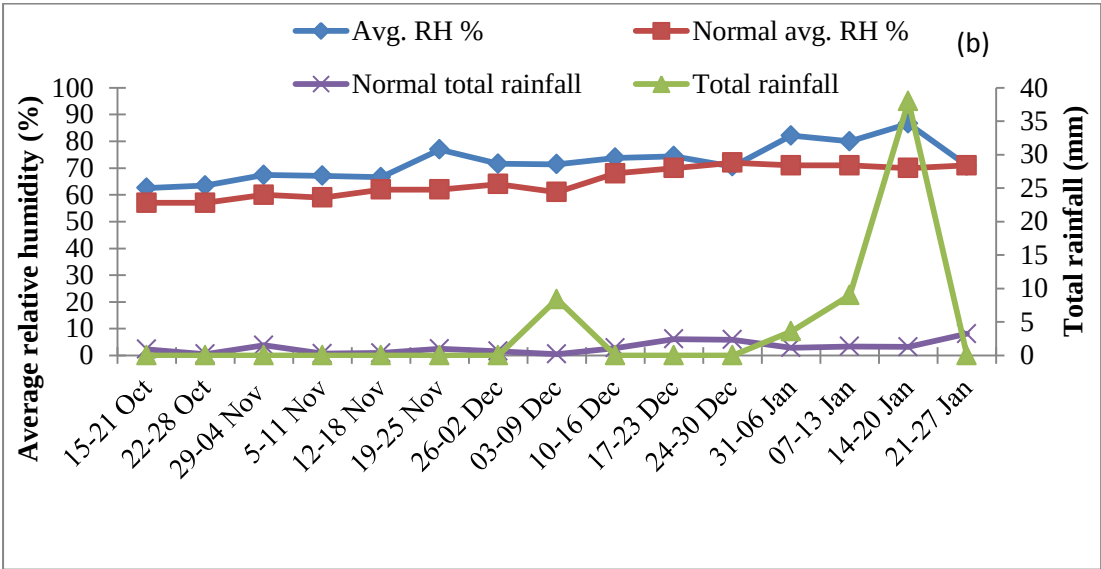
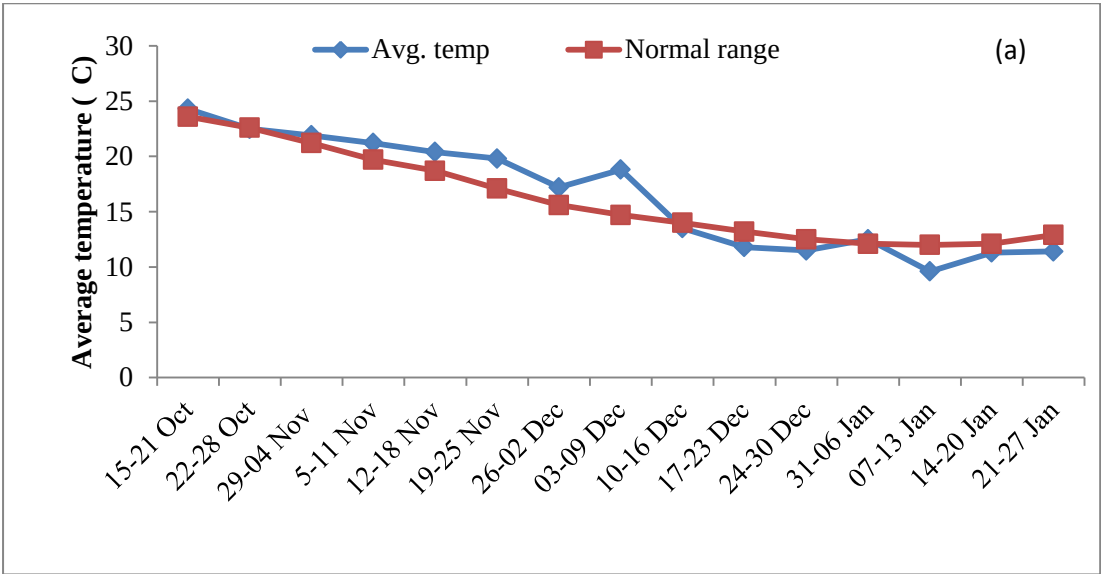
Treat ment	Graded tuber yield												Discarded production (%)								
	Large			Medium			Small			Smaller			Green % (a)			Blemished % (b)			Discarded % (a+b)		
Year	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Pooled
S ₂₀ D ₂₀	30.1a	33.4a	31.7a	49.0a	53.7a	51.4a	58.3a	60.8a	59.6a	70.0a	73.0a	71.5a	2.80d	2.50c	2.65c	1.41c	3.46b	2.44d	4.21d	5.96bcd	5.09c
S ₃₅ D ₂₀	28.5ab	31.5a	30.0a	50.1a	52.9ab	51.5a	56.4ab	59.7ab	58.1ab	67.3ab	71.6a	69.4ab	2.56d	2.40c	2.48c	2.40b	2.57b	2.49cd	4.96cd	4.97d	4.97c
S ₅₀ D ₂₀	21.5cde	23.0abcd	22.2bc	42.7bc	42.2bcd	42.4bc	51.2abcd	54.0abc	52.6bc	60.1bc	63.3ab	61.7cd	2.90d	2.67bc	2.79c	3.10b	2.67b	2.89bcd	6.00c	5.34cd	5.67bc
S ₂₀ D ₃₀	23.3cd	22.5abcd	22.9bc	45.2ab	44.3abcd	44.7b	54.2abc	57.5ab	55.8ab	64.8ab	65.3ab	65.0abc	2.83d	2.66bc	2.75c	2.58b	3.34b	2.96bcd	5.40c	5.99bcd	5.70bc
S ₃₅ D ₃₀	17.9ef	18.6bcd	18.3cde	38.6cd	37.7cde	38.2cd	48.0cd	48.5bcd	48.3cd	58.8bc	63.0ab	60.9cd	4.60a	4.00ab	4.30a	3.44b	3.10b	3.27bc	8.04b	7.10bc	7.57b
S ₅₀ D ₃₀	14.2fg	18.1bcd	16.1de	34.1de	33.6de	33.9de	45.7de	43.2cde	44.5de	54.4cd	59.3b	56.9d	4.30abc	4.10ab	4.20ab	3.33b	3.40b	3.37b	7.63b	7.50b	7.57b
S ₂₀ D ₄₀	20.3de	23.5abc	21.9bcd	41.8bc	42.8abcd	42.3bc	52.7abcd	53.2abc	52.9bc	64.0ab	64.7ab	64.4bc	3.07bcd	2.59bc	2.83c	2.58b	3.50b	3.04bcd	5.66c	6.09bcd	5.88bc
S ₃₅ D ₄₀	13.2g	15.8cd	14.5ef	32.0e	29.7ef	30.9e	40.2ef	40.6de	40.4ef	54.8cd	56.4bc	55.6d	4.40ab	3.90ab	4.15ab	3.53b	3.54b	3.54b	7.93b	7.44bc	7.69b
S ₅₀ D ₄₀	8.2h	10.7d	9.4f	21.1f	21.7f	21.4f	35.7f	35.7e	35.7f	48.4d	48.4c	48.4e	4.70a	4.30a	4.50a	3.79b	3.70b	3.75b	8.49b	8.00b	8.25b
Control	25.2bc	29.8ab	27.5ab	45.9ab	45.4abc	44.7b	49.9bcd	48.0bcd	52.1bc	64.0ab	67.4ab	66.8abc	3.00cd	3.00abc	3.00bc	11.83a	10.33a	11.08a	14.83a	13.33a	14.08a

* Column mean with different letters differ significantly at p-value <0.05.

Table 6: Tuber dry weight (g per 100 g of fresh weight), dry tuber yield (kg ha⁻¹), root dry weight per plant (g) and source/sink ratio for potato plantings in the year 2011 and 2012.

Treatment	Tuber dry weight (g per 100 g)			Dry tuber yield (kg ha ⁻¹)			Root dry weight (g plant ⁻¹)			Source/Sink ratio		
Year	2011	2012	Pooled	2011	2012	Average	2011	2012	Pooled	2011	2012	Pooled
S ₂₀ D ₂₀	15.6cd	16.1bc	15.9cd	3243.9	3556.5	3400.2	2.85a	3.10a	2.98a	0.411b	0.388b	0.399b
S ₃₅ D ₂₀	16.8bc	17.5ab	17.2bc	3402.0	3774.2	3588.1	2.66a	2.90a	2.78a	0.381bc	0.350bc	0.365bc
S ₅₀ D ₂₀	17.7abc	18.2a	18.0ab	3112.2	3321.5	3216.9	1.64bc	1.66bcd	1.65bc	0.345bc	0.334bc	0.339bc
S ₂₀ D ₃₀	16.8bc	17.5ab	17.2bc	3155.1	3344.8	3250.0	2.32ab	2.77ab	2.55a	0.369bc	0.341bc	0.355bc
S ₃₅ D ₃₀	17.6abc	18.3a	18.0ab	2879.5	3072.6	2976.1	1.26c	1.44cd	1.35c	0.329c	0.318c	0.323c
S ₅₀ D ₃₀	18.2ab	18.8a	18.5ab	2695.9	2899.6	2797.8	1.12c	1.37cd	1.25c	0.330c	0.315c	0.322c
S ₂₀ D ₄₀	17.0abc	17.7ab	17.4abc	3046.1	3259.2	3152.7	2.28ab	2.40abc	2.34ab	0.363bc	0.334bc	0.349bc
S ₃₅ D ₄₀	18.2ab	18.8a	18.5ab	2551.6	2680.9	2616.3	0.99c	1.03d	1.01c	0.323c	0.336bc	0.330c
S ₅₀ D ₄₀	19.0a	19.3a	19.1a	2150.6	2252.1	2201.4	0.79c	0.87d	0.83c	0.371bc	0.391b	0.381bc
Control	14.2d	15.5c	14.9d	2539.0	2954.3	2746.7	2.92a	3.30a	3.11a	0.545a	0.483a	0.514a
p-value	<0.05	<0.05	<0.05	-	-	-	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Column mean with different letters differ significantly at p-value <0.05.



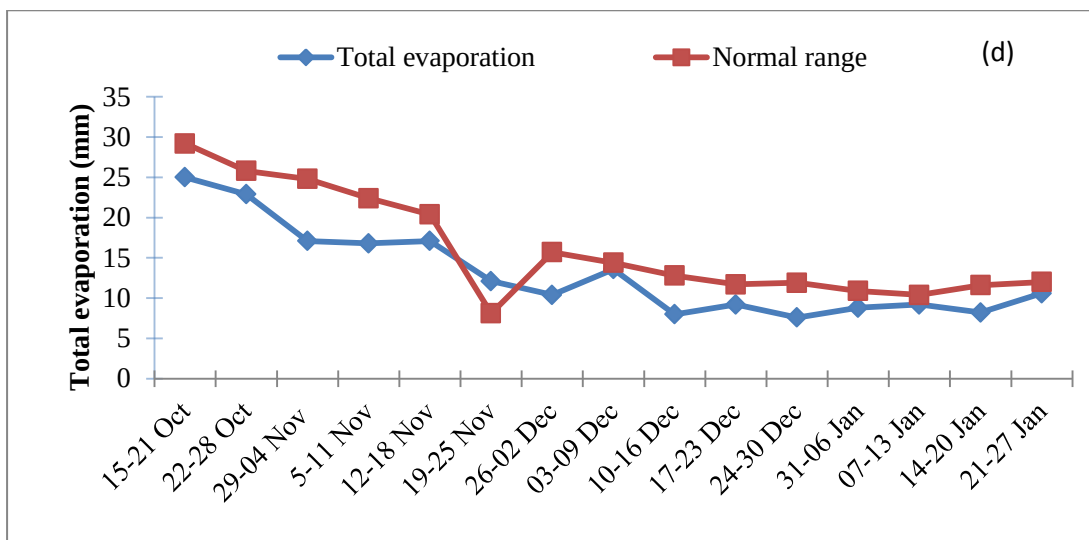
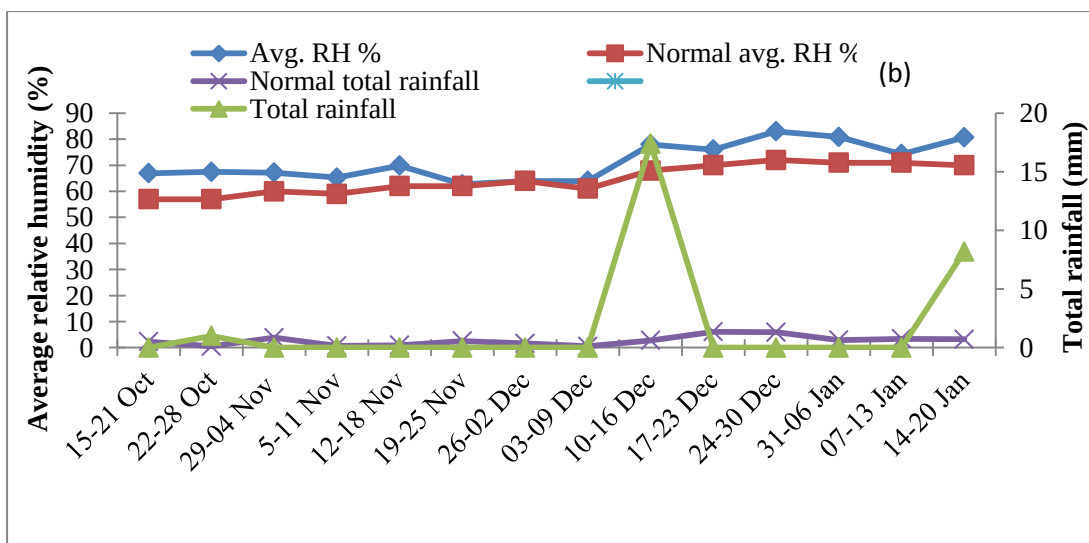
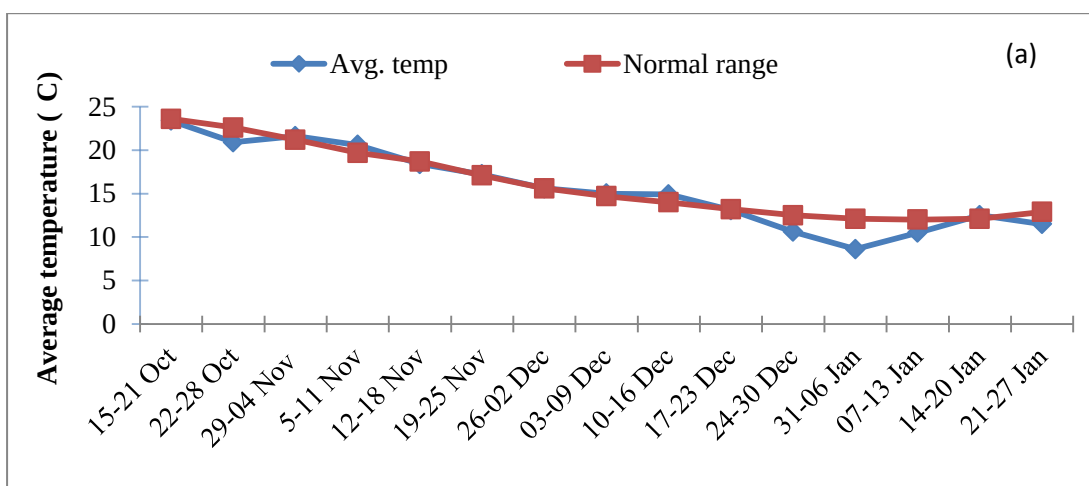


Fig. 1. Average temperature (a), RH % & total rainfall (b), sunshine (c) and evaporation (d) with their respective average normal range (last 30 years) during the potato growing season 2011-12



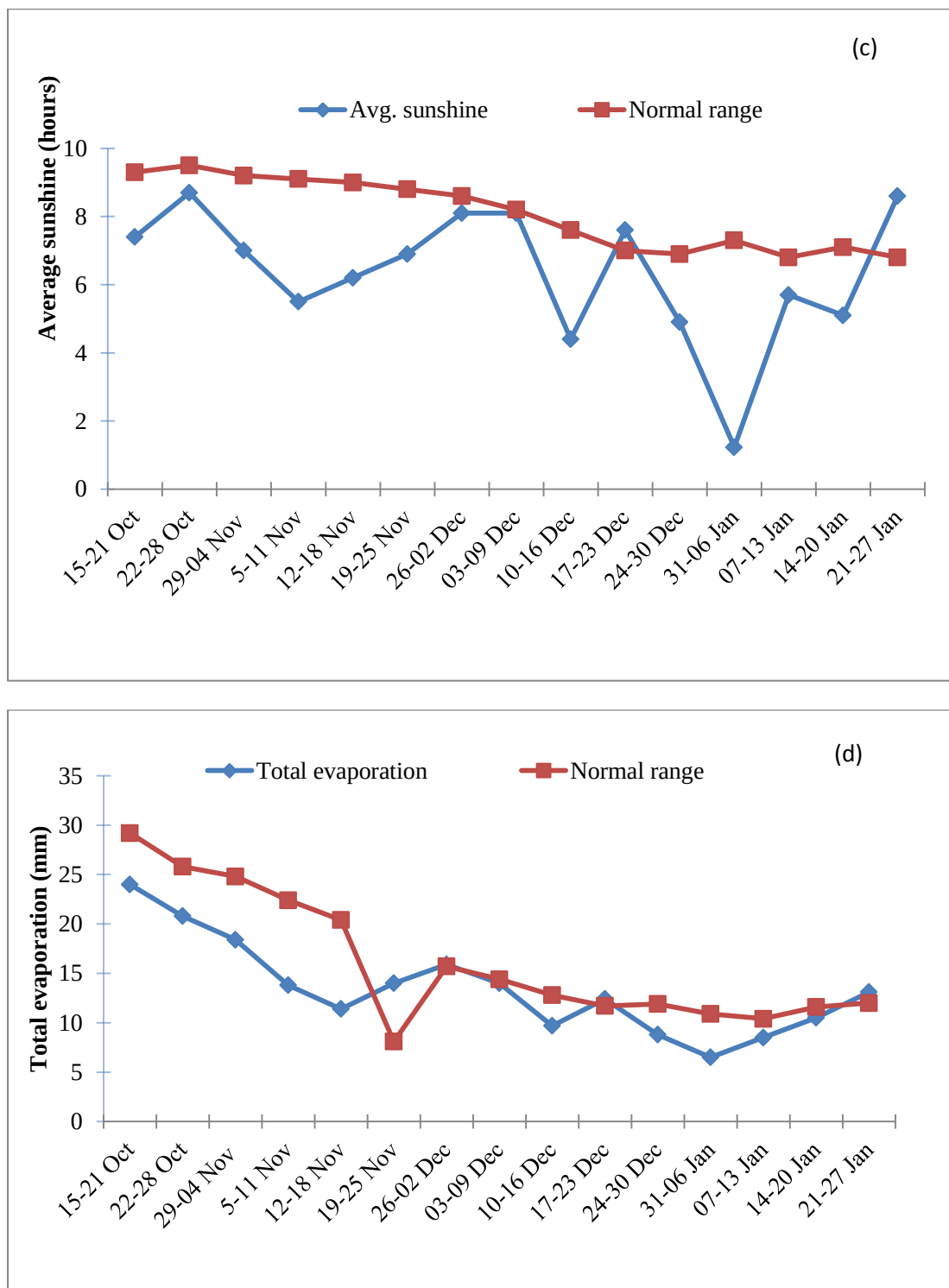


Fig. 2. Average temperature (a), RH % & total rainfall (b), sunshine (c) and evaporation (d) with their respective average normal range (last 30 years) during the potato growing season 2012-13

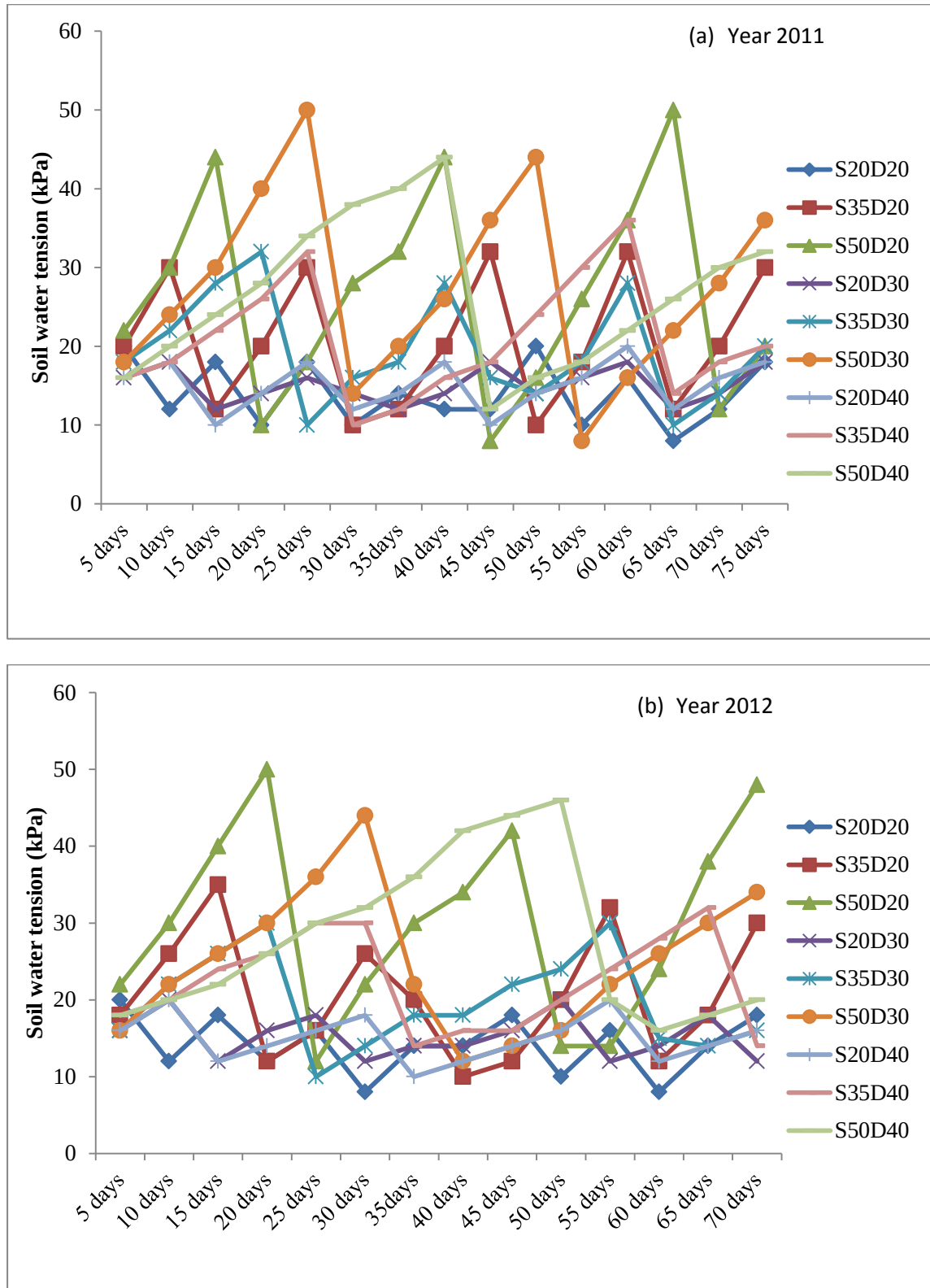


Fig. 3. Periodic variation of soil water tension for different treatments after the emergence of crop (recording of observations for tensiometer readings were started after complete crop emergence) during potato plantings for the year 2011 (a) and 2012 (b)

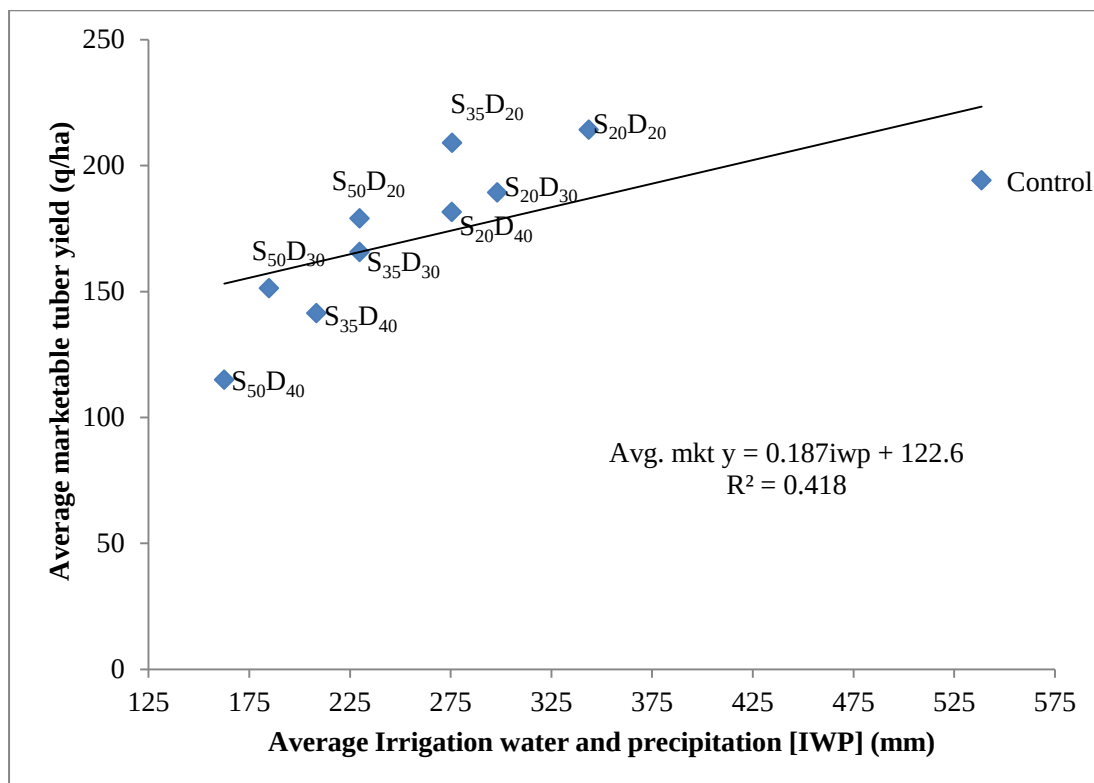


Fig.4. Relationship between marketable tuber yield (Average of year 2011 & 2012) and Irrigation water applied (average of year 2011 & 2012) for different treatments

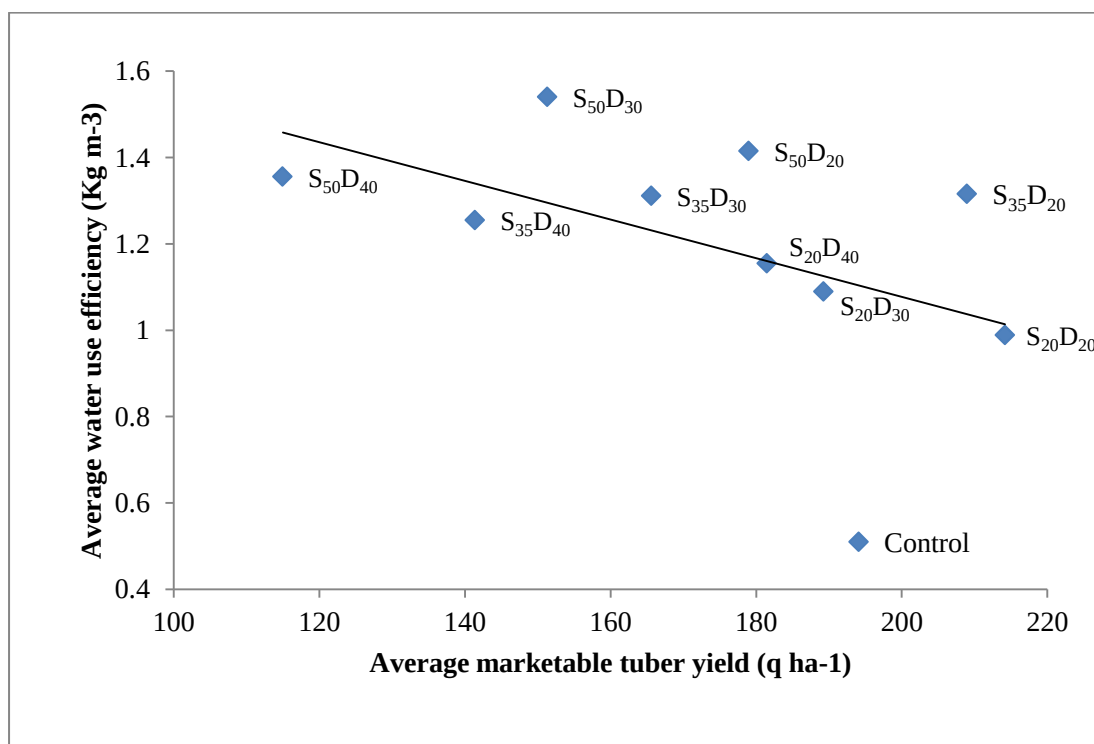
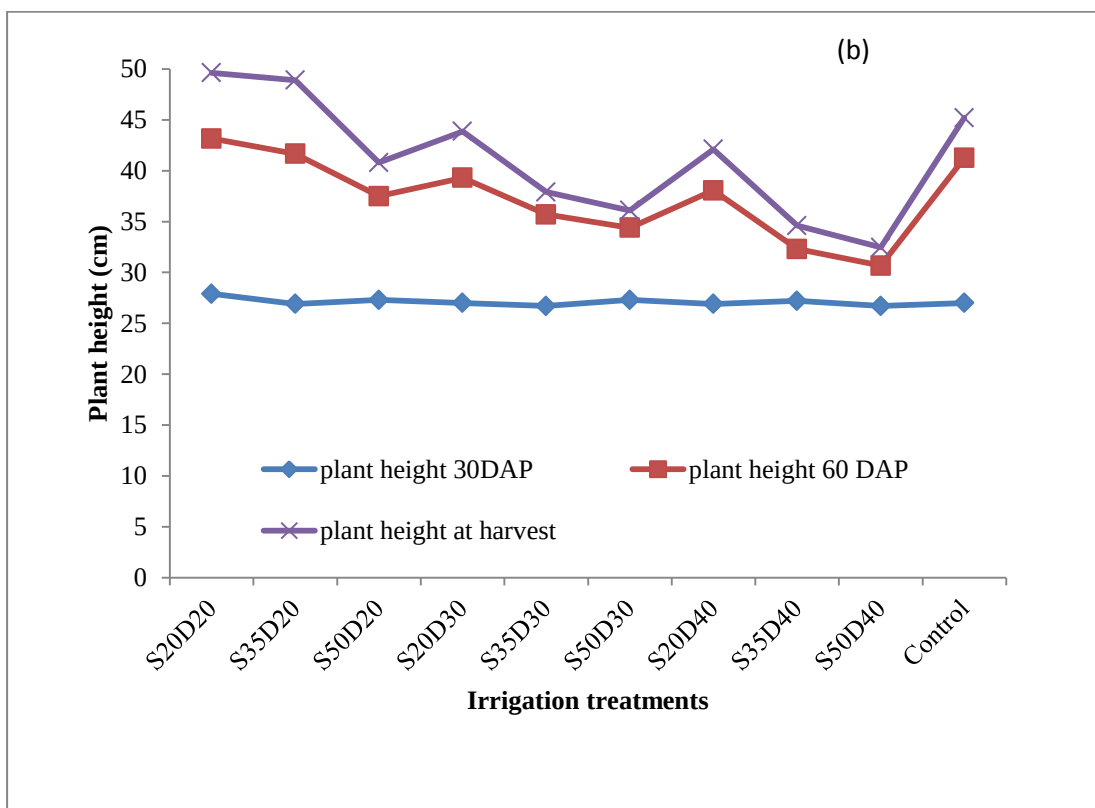
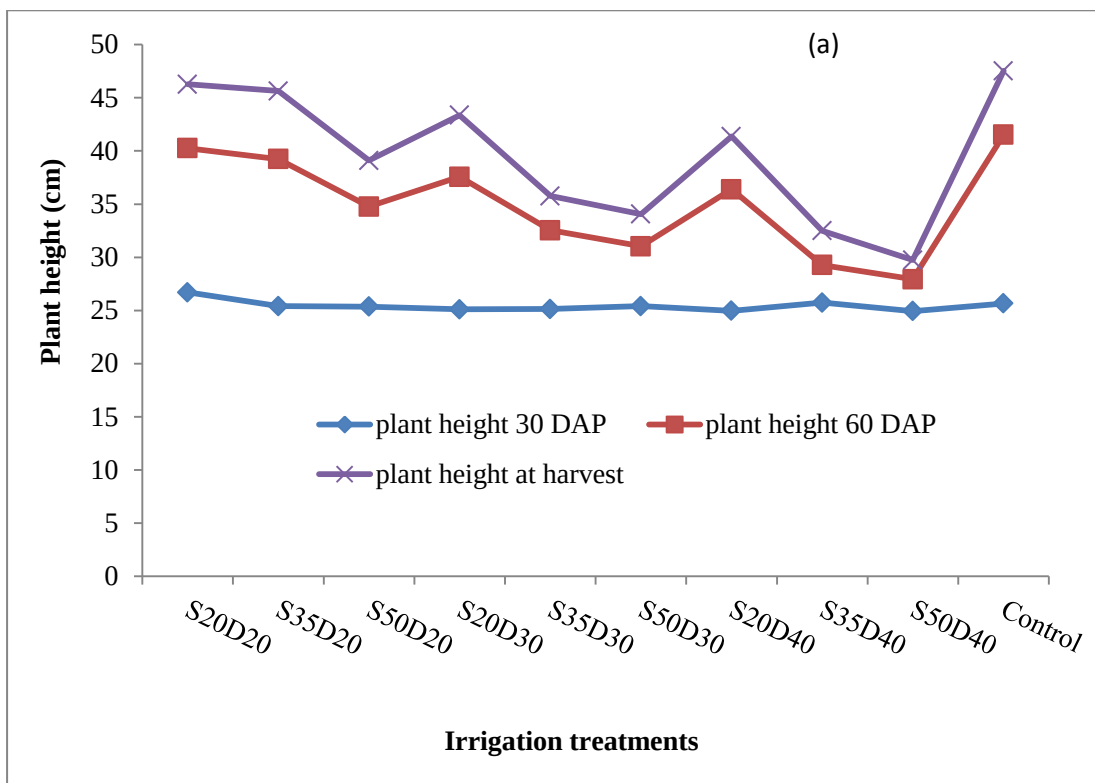


Fig.5. Relationship between marketable tuber yield (average of 2011 & 2012) and water use efficiency (average of 2011 & 2012) for different treatments



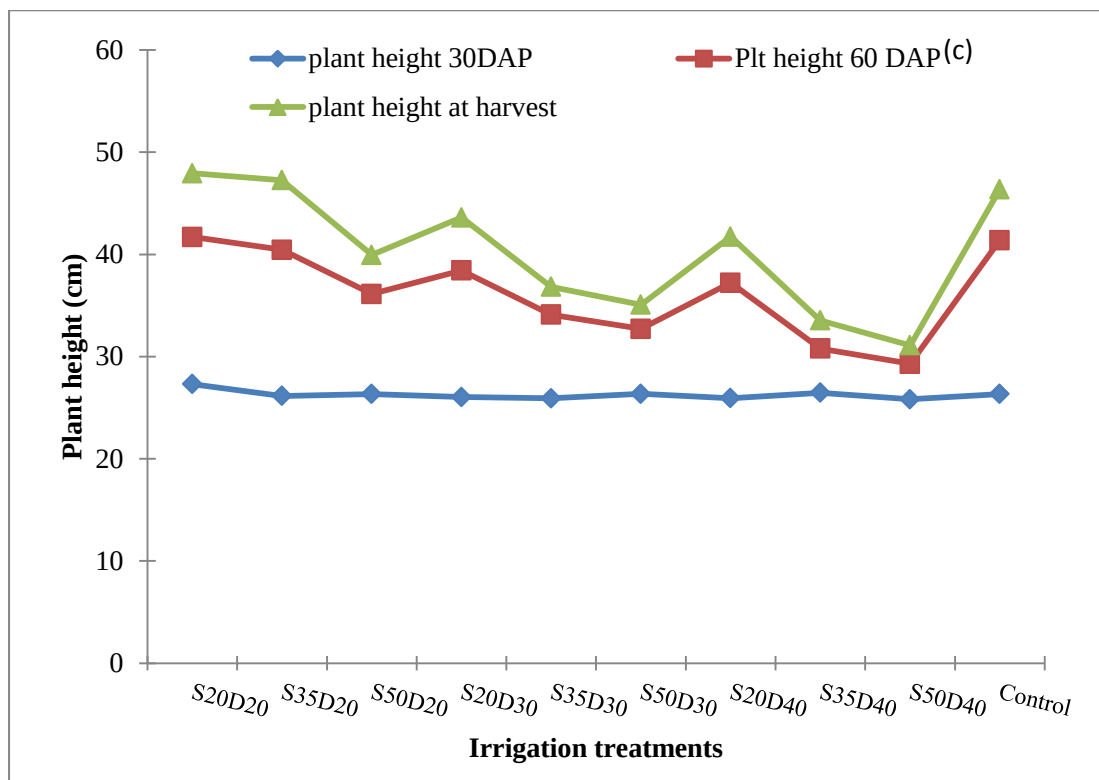


Fig. 6. Plant height at 30, 60 DAP and at the time of harvest during the year 2011 (a), 2012 (b) & pooled data (c).

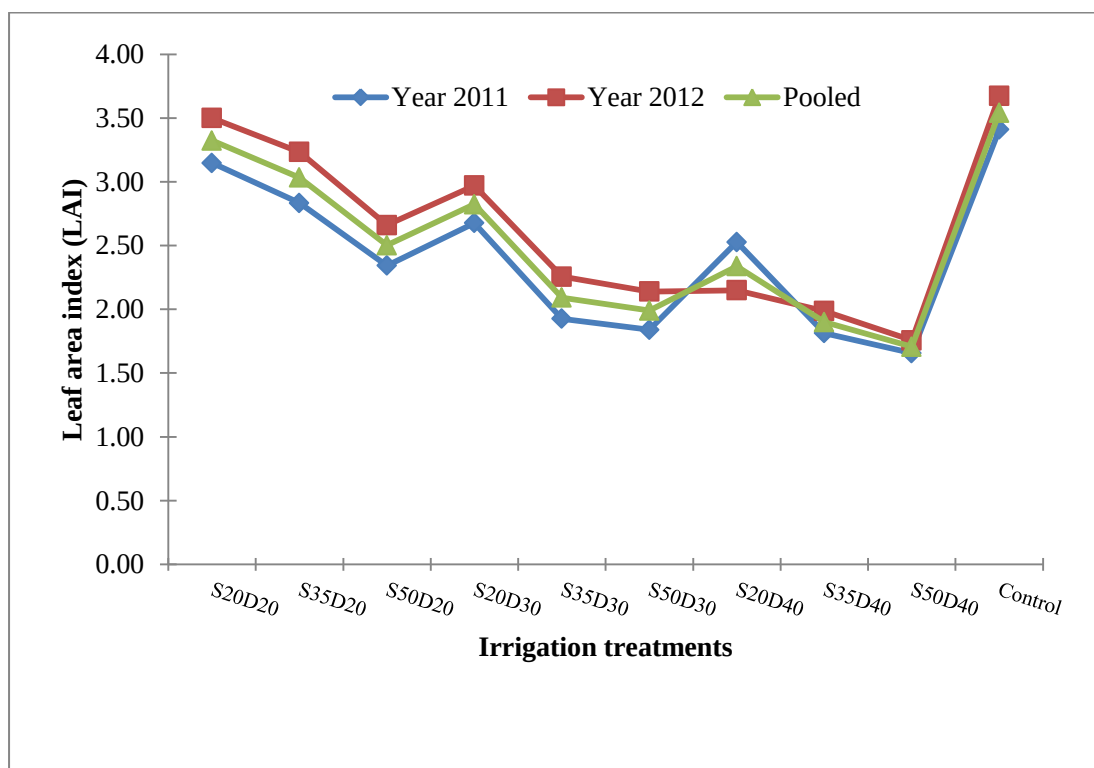


Fig. 7. Leaf area index for the year 2011& 2012 and pooled data.

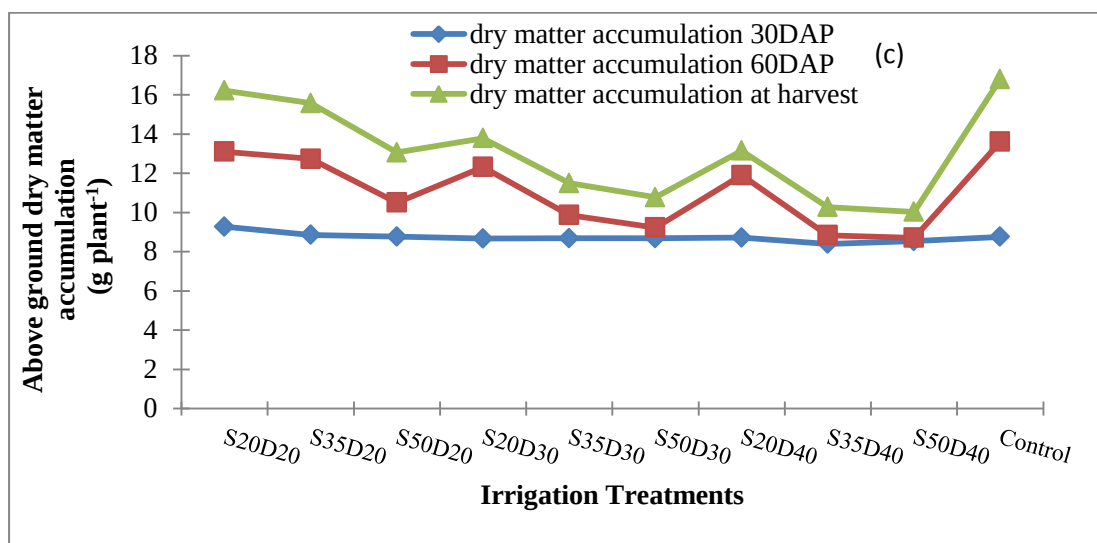
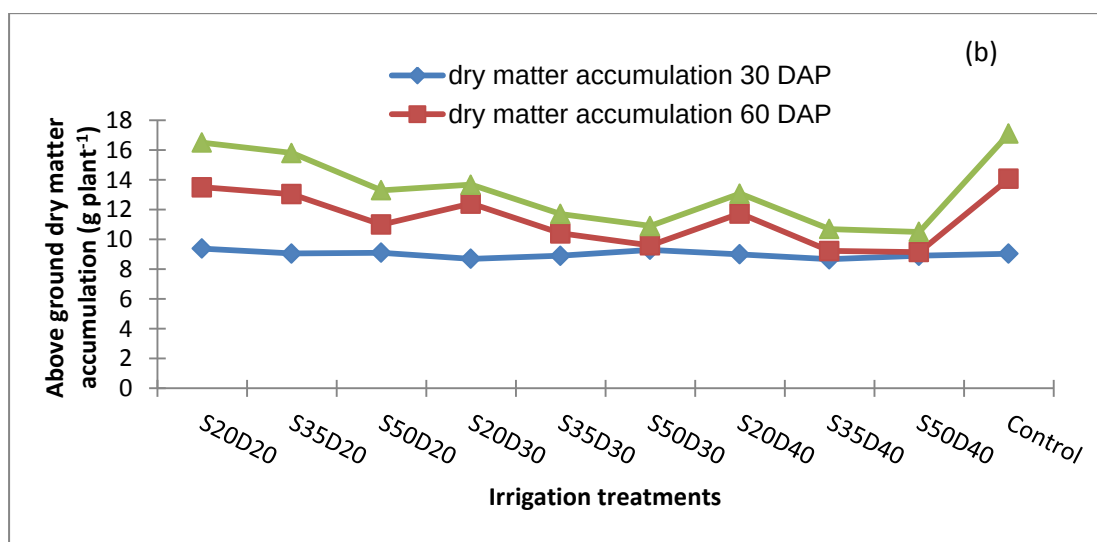
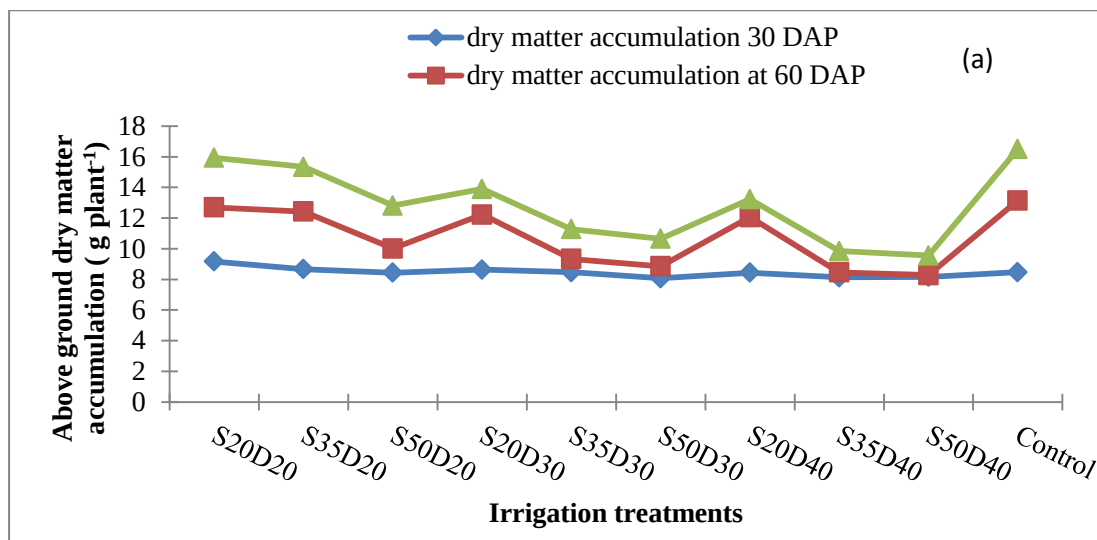


Fig. 8. Above ground dry matter accumulation (g plant⁻¹) at 30, 60 DAP & at the time of harvest during 2011(a), 2012(b) and pooled data (c) for different treatments

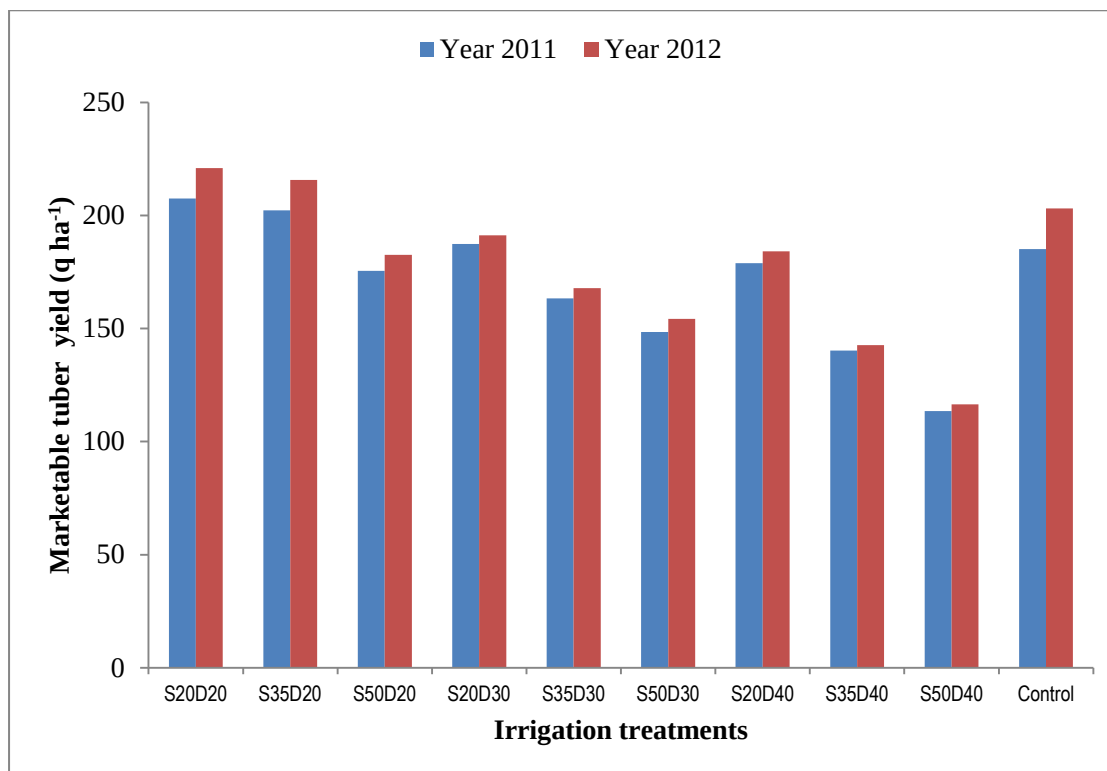


Fig. 9. Comparative marketable tuber yield (q ha⁻¹) for potato plantings in the year 2011 and 2012

IRRIGATION SCHEDULING UNDER DIFFERENT CROP ESTABLISHMENT METHODS IN NORTH-WESTERN PLAINS OF INDIA

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Abstract: A field investigation was conducted to find out the optimal irrigation schedule under different crop establishment methods in sandy loam soil in North-Western plains of India during 2012-13 and 2013-14. The experiment comprised of climatic and soil matric potential based irrigation treatments: I₁: IW/CPE: 1.00, I₂: IW/CPE: 1.25, I₃: IW/CPE: 1.50, I₄: S₃₅D₂₀ and I₅: control (farmers practice). These treatments were compared under ridge-furrow (M₁) and bed-furrow planting (M₂) system. The experiment was laid in split plot design with four replications. The ridge-furrow method of planting showed its advantage over the bed-furrow method of planting in terms of recording higher WUE, average tuber weight, marketable tuber yield, large and medium sized tuber yield, plant height at 60, 75 DAP and at harvest as well as above ground dry weight accumulation at the time of harvest. Almost three times higher water use efficiency was recorded by S₃₅D₂₀ as compared to control treatment (farmer's practice) under M₁. This irrigation treatment was superior in terms of plant height, above ground DMA at 60 DAP and at harvest, graded and marketable tuber yield and has lower discarded percent of tubers among all other treatments. The results suggest that scheduling irrigation based on soil matric potential through targeting -35 kPa SMP by tensiometer installing at soil depth of 20 cm under ridge-furrow irrigation system was better option under North-Western plains of India.

1. Introduction: Potato is a principal crop under majority of agro-climatic conditions owing to its indispensable qualities of wider planting adaptability and shorter life span. In India there is considerable unrealized potential to increase potato production (Scott and Suarez, 2011). Central Potato research Institute of India projects average growth rate of 3.8% for future potato production in India by 2030 (CPRI, 2011). In the Indian state of Punjab (part of North-Western India) the area and production under potato has witnessed five and eight times increase, respectively in the last fifty years with present of production of about two million tonnes.

The potato crop is planted on the ridges/hills and earthing up is done on both the sides of ridge for better stolon formation, tuber initiation and tuber bulking. Mainly the crop is irrigated through furrow irrigation but this greatly varies with the methods of planting of crop. Under furrow irrigation, most of the irrigation water infiltrate down the root zone area without its proper absorption by the roots. It has been observed that surface irrigation methods are used in more than 80% of the world's irrigated lands in spite of 40-50% field level application efficiency (Von Westarp et al., 2004). Bed planting has been found beneficial and it also saves water (Fisher, 1995). Ridge and bed planting methods have extensively been used in

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potato cultivation and as such many scientists have conducted research on water use efficiency and its effect on crop yield and its quality (Singh et al., 2010; Bombik et al., 2013; Singh and Sood, 2013; Vitos, 2013). However, bed planting has been proved to be more useful in terms of water use efficiency and yield (Sidhu et al., 2005; Harms and Konschuh 2010; Singh et al., 2010; Qasim et al., 2013).

The water scarcities have been forecasted in agriculture and non agriculture sectors with climate change (Hira, 2009). Moreover, there is increased demand of water for organic and non organic agriculture sector, thereby making it necessary to conduct more research on irrigation schedule on crops. Keeping in view the increasing demand of water as well as increasing area under potato crop, there is a need for evaluating accurate irrigation scheduling to improve irrigation water use and energy use efficiency (Gulati and Singh, 2011).

Scheduling of irrigation in any crop depends upon soil type, crop variety, methods of planting as well as location. In India, pan evaporation based irrigation schedule has been recommended for potato cultivation by Directorate of All India coordinated project for research on water management. But more recently, Medici et al., (2014) has suggested that the irrigation schedule based on the approach of soil water tension which requires simple instrument like tensiometer can be an efficient criterion for irrigation level along with other ones. A preliminary study conducted by the authors (unpublished) has established scheduling of irrigation at SWT of 35 kPa for higher yield and better tuber quality under furrow-ridge irrigation system for sandy-loam soils in the North-Western Indian plains.

Considering all these factors, this study was undertaken with the objective to find out the best schedule of irrigation for maximizing water use efficiency (WUE) under different crop establishment methods in the North-Western plains of India. The study compared different irrigation schedules under furrow-ridge and furrow-bed planting systems

2.0 Material and Methods:

2.1. Site, climate and soil

The investigation was undertaken on a typic Ustipsamment soil at Vegetable Research Farm, Department of Vegetable Science, Punjab Agricultural University, Ludhiana (Punjab) India (30° 53' N, 75° 49' E) for two potato growing seasons (October to January) in 2012-13 and 2013-14. The climate of Ludhiana is subtropical, semi-arid with an annual rainfall of 755 mm. Major part of the annual rainfall is received during June to September known as monsoon. The mean monthly temperatures during the potato growing season (October-January) varied from 8.6 to 23.4°C during first and 10.3 to 25.7°C in second season. Soil type was sandy loam with composition of 71 % sand, 19% silt and 10% clay. The experimental site in 2012 has: pH 7.9, electrical conductivity: 0.24 dS m⁻¹, organic C 3.5 g kg⁻¹, 0.5 M NaHCO₃ extractable P (Olsen et al., 1954) 8.0 mg kg⁻¹ and K (Pratt, 1965) 172.5

mg kg⁻¹, and pH: 7.8, EC: 0.21 dS m⁻¹, OC: 3.5 g kg⁻¹, extractable P: 7.75 mg kg⁻¹ and K: 171.0 mg kg⁻¹ in the year 2013. The saturated and unsaturated hydraulic conductivity (Smettem and Clothier, 1989) were measured using disc permeameter (Table 1) during 2012 and 2013 before the commencement of experiment.

2.2. Field Experiment Design

The seed tubers (40 to 50 g) of potato were planted on 18th October 2012 and 15th October 2013. The experiments were conducted in split plot design with four replications. There were two main plots comprising ridge-furrow (M₁) and bed-furrow planting (M₂) treatments randomized within. Each ridge was spaced at 60 cm from another ridge and it was followed by a furrow in ridge-furrow irrigation system. Beds with 85 cm top and 120 cm bottom width were prepared each followed by a furrow under bed planting method. Both of ridge-furrow and bed-furrow plots were prepared using semi-automatic potato planter and bed planter respectively. Plots measuring 10.0 m × 5.2 m (gross plot size) comprising eight ridges each followed by a furrow under ridge-furrow and four beds each followed by a furrow under bed planting method of planting were prepared. Two rows were planted on each bed. Two metre wide border was kept between two adjacent plots as well from irrigation channel to prevent unwanted water seepage. An early bulking cultivar, Kufri Pukhraj comprised the plant material. Disease free tubers of this cultivar were planted 20 cm apart on top of ridges. After planting potato crop, 5 cm of common irrigation water was given to ridge-furrow plots and 4 cm to bed plots except control plots which received 11 cm and 9 cm water after planting under ridge-furrow and bed planted plots, respectively for proper establishment of the crop (Table 2). The treatments consisted of five irrigation levels: I₁; IWCPE (Irrigation water to cumulative pan evaporation) ratio 1.0, I₂; IWCPE ratio 1.25, I₃; IWCPE ratio 1.5, I₄; 35kPa×20cm (tensiometer installed at 20 cm soil depth maintaining SMP of -35 kPa) and I₅; control (farmers practice in the region). A performa was prepared and filled after polling and personal interviews with the farmers for collecting information regarding crop and irrigation management practices followed by them before finalizing irrigation scheduling for control treatment.

2.3. Crop management

Pre-sprouted seed tubers weighing approximately 45g each were planted at the spacing of 60×20 cm under ridge-furrow and 45×27 cm on the bed (equivalent to a maintaining equal plant density of 8.33 plants m⁻²). Before planting, potato seed tubers were dipped in fungicide Monceron 0.25% solution for 10 minutes and spread thereafter under shade for drying. Planting was done in the dry soil for control plot and in pre-irrigated soil for all other treatments during both the years. All plants emerged 19 and 21 days after planting during the first and second years respectively. Standard crop management practices were

followed for raising successful crop. Potato vines were dehaulmed 90 days after planting and tubers were lifted 15 days after dehaulming for hardening of tubers. The tubers were harvested on 31 January 2013 and 28 January 2014. All the required growth and yield parameters were recorded periodically.

2.4. Irrigation treatments:

Irrigation was applied using good quality water (EC: 0.5 dS m⁻¹) sourced from the tube-well installed near the experimental area. Irrigation was given to facilitate the rooting and establishment of the crop for its complete emergence and for this purpose all plots received 5 cm of pre-plant irrigation water except control plots. The control plots received 11 and 9 cm and other plots received 5 and 4 cm post-plant irrigation water under ridge-furrow and bed-furrow planting system, respectively. After these common irrigations, rest irrigations were applied as per the treatment schedule. However, the control treatment received first irrigation 10 days after complete emergence and remaining irrigations at an interval of 12 days (Table 2). Additional irrigation was given to control plots during the days when there were chances of frost occurrence. Only rainfall exceeding 5 mm within 25 hr was considered effective and included in the calculations for total water use.

Dial vacuum gauge tensiometers were installed at 20 cm depth on the ridge (from the top surface of the ridge) between two plants in the middle potato row of each I₄ plot. Monitoring of tensiometers was started regularly for SMP reading after the complete emergence of the crop. The readings were observed daily between 8.00 a.m. and 9.30 a.m. and irrigation was applied thereafter as per requirement of the treatment. The irrigation to the I₁ to I₃ treatment plots was applied based on the targeted IW:CPE ratios.

2.5. Data Collection:

The data was collected periodically on plant height, above ground dry matter accumulation (DMA) and LAI in randomly selected five plants. The plant height and DMA was recorded at 30, 60 DAP and at the time of harvest for plant height. Additionally plant height was recorded at 75 DAP. The LAI was recorded 60 DAP. The DMA was estimated by collecting above-ground plant samples making them dry at constant temperature of 65°C. Similarly, 100 g tuber samples were dried for estimating tuber dry weight. To determine root mass density at harvest stage, root samples were taken carefully with the help of pvc pipe of about 5 inch diameter by collecting undisturbed soil without disturbing sample and washed gently by using 40 mesh nylon sieve. Root dry weight was measured indoors after the root samples were oven-dried at 60°C for 24 hrs.

At tuber harvest, 50 plants from each plot were harvested by randomly selecting middle three rows of potatoes; the tubers were picked manually, counted, graded based on the tuber weight and weighed to determine graded, marketable tuber yield, and average tuber

weight. Malformed, diseased tubers and tubers that weighed <15 g were considered blemished tubers and tubers showing greening disorder were considered as green tubers. Discarded production was determined as percent weight of malformed, diseased, undersized and green tubers of the total tuber yield.

The tuber dry yield (kg ha^{-1}), WUE (Kg m^{-3}) and source/sink ratio were calculated. The tuber dry yield was calculated by multiplying tuber dry weight per 100g and marketable tuber yield. The WUE which gives an indication of water productivity was computed as per the method suggested by Xie et al.,(2012). Source/sink ratio is calculated as per the method used by Ierna and Mauromicale, 2012.

$$\text{WUE} = \frac{\text{Tuber dry yield}}{\text{Total water applied}}$$

where, total water applied = supplemental irrigation plus rainfall.

$$\text{Source/Sink ratio} = \frac{\text{Canopy dry weight}}{\text{Tuber dry weight}}$$

where, canopy dry weight was measured when maximum leaf area index (75 DAP during both the years) was achieved and the tuber dry weight measured at the end of the crop cycle.

2.6. Meteorological data

Meteorological data were recorded at meteorological station situated about 500 metre distance from the experimental site. Weekly average temperature, relative humidity, sunshine and total rainfall and evaporation during the potato growing period from October,15 to January, 31 in 2012-13 and 2013-14 seasons, respectively were recorded (Fig. 1 & Fig. 2).

2.7. Data Analysis

Two years data were subjected to analysis of variance (ANOVA) (Gomez and Gomez, 2010) based on PROC GLM (SAS software 9.1). Duncan's multiple range tests at $p=0.05$ was applied to compare the means of different treatments. Before ANOVA, percentage data of discarded production, green and blemished per cent and data for source to sink ratio (by converting into percent) were transformed into angular values by using $\arcsin\sqrt{\%}$. The actual values are shown.

2.8. Rainfall

2012-13: Total rainfall was not uniformly distributed and was lower than the normal range during 2012-13 potato growing season. There were two events of rainfall above 5mm measuring 25.6 mm of water in the IIIrd week of December (17.2 mm) and IIIrd week of January (8.2 mm). But the rainfall that occurred in IIIrd week of January was not considered for further calculations as this event occurred when the crop had approached maturity.

During the 2013-14 potato growing period, there were three effective events of rainfall above 5mm measuring in total 48.5 mm water. One event of rainfall (12 mm) occurred in the Ist week of November and second event (10.4 mm) occurred in last week of

December. The rainfall that occurred in the IInd and IIIrd week of January (26.1 mm) were not of much use as crop was approaching near maturity and the same was considered ineffective for doing further calculations.

3.0 Results and Discussion:

3.1 Irrigation water, water use efficiency (WUE) and irrigation water use efficiency (WUEi)

Highest irrigation water was used under the control during both the years and methods (Table 2). Total water volume utilized varied from 2524 to 5124 m³ ha⁻¹ during first year and 2154 to 5524 m³ ha⁻¹ during the second year under ridge-furrow planting method. The corresponding values under bed-furrow method of planting were 2274 to 4224 and 2354 to 4274 m³ ha⁻¹ during first and second year, respectively. Approximately 10 % lower water volume was utilized under bed planting than that of ridge planting during both the years which may. The analysis of data showed that water use efficiency was significantly higher under ridge planting (M₁) as compared to bed planting method during the second year, although the corresponding values during first year were statistically at par. Among all the irrigation treatments, I₄ recorded significantly higher water use efficiency both under M₁ and M₂ methods of planting during both the years. Treatment I₄, recorded 189% higher water use efficiency as compared to under control in addition to saving of 51% water volume during the first year and the corresponding values during the second year were 185% and 53%. The control treatment recorded lowest water use efficiency during both the years of planting which may be due to supply of maximum quantity of water volume under the control treatment during both the years.

Irrigation water use efficiency (WUEi) did not vary with the methods of planting. Treatment I₄, recorded significantly higher WUEi among all the irrigation treatments during both the years as well as under both the planting methods. Treatment, I₄ recorded 138% higher WUEi than that of control as 52% water volume was saved during the first year and the corresponding values during the second year were 167% and 60% under ridge-furrow method of planting (M₁). The corresponding values for the same treatment in the second year under bed-furrow method of planting (M₂) were 123% & 48% and 129% & 53%. Sidhu *et al.* (2005) also recorded higher water use efficiency by maintaining soil matric suction of 20±2 kPa under different planting methods.

3.2 Average tuber weight and marketable tuber yield

The analysis of data revealed that average tuber weight was significantly higher under ridge-furrow (M₁) in comparison to the bed-furrow planting method during the second year. It was significantly higher for I₃, I₄ and I₅ under M₁ method and I₄ treatment under M₂ method of planting during both the years and for I₅ treatment under M₂ during the second year. The

treatments I₃, I₄ and I₅ under M₁ method of planting have received higher amount of irrigation water which may probably have resulted in better moisture content in the root zone for better growth and development of tubers. Similarly, the treatment I₄ under bed-furrow method of planting may have received optimum soil moisture for the better tuber development. Singh and Sood (2013) also obtained higher average tuber weight in the traditional ridge-furrow planting as compared to the raised bed planting. The method of planting significantly affected the marketable tuber yield which was significantly higher under M₁ i.e. ridge-furrow planting method as compared to M₂, method of planting. The lower marketable tuber yield under bed planted crop may be due to moisture stress in the vicinity of the root zone area as the plantation was near the centre of beds. Sidhu et al., (2005) also reported lower tuber yield under 90 cm wide beds as compared to the 60 cm wide beds. In our study also bed width on the top was 85 cm. However, our finding is in contrary to the results of Qasim *et al.* (2013), who had reported higher tuber yield under wide beds as compared to the ridge planted crop. Among the various irrigation treatments, marketable tuber yield was significantly higher for I₄ treatment under both the planting methods and years and this treatment was statistically at par with I₅ treatment during the second year. Treatment I₄ recorded 13.1% and 12.6% higher tuber yield than that of control under ridge-furrow planting system during first and second years, respectively and the corresponding values under bed-furrow planting method were 15.4% and 8.3%. The treatment I₅ under M₂ method of planting also recorded significantly higher marketable tuber yield which was statistically at par with I₃ treatment during the second year. The recording of higher marketable tuber yield under ridge-furrow planting method evidenced the advantage of this method over the bed-furrow planting. The irrigation treatments which registered higher marketable tuber yield may probably have received the proper amount of irrigation water for keeping optimum soil moisture in the root zone for higher production of healthy tubers.

3.3 Graded tuber yield

Graded tuber yield was significantly affected by method of planting except for small size tubers during both the years and smaller size tubers for first year. Among the two methods, ridge-furrow planting method (M₁) recorded significantly higher tuber yield for large and medium sized tubers during both the years. However, M₂ showed significantly higher tuber yield for smaller sized tubers during the second year. Among different irrigation treatments, I₄ treatment during both the years and I₃ and I₅ during the first year under M₁ method of planting recorded significantly higher large sized tuber yield. Under M₂ method of planting, I₄ recorded significantly higher large sized tuber yield and treatments, I₃ and I₅ for

second year were statistically at par with I_4 . Treatment, I_4 recorded significantly higher medium and small sized tuber yield both under M_1 and M_2 methods during two years. Under M_2 method of planting, I_5 treatment recorded significantly higher medium and small sized tuber yield during the second year. Medium sized tubers yield for I_3 treatment during second year under M_2 was also significantly higher. It is evident that the I_3 , I_4 and I_5 treatments recorded higher large and medium sized tuber yield which indicates that under these treatment, tubers gathered higher biomass. It may probably because of proper moisture in the root zone which may have resulted in better growth and development of tubers. Similarly, Singh and Sood (2013) and Singh et al., (2010) also recorded higher tuber yield of large sized (>75g) tubers under conventional ridge-furrow system as compared to raised bed planting. In our study, medium size tubers were >75g, thus our results were similar to earlier findings. All the irrigation treatments under M_1 recorded statistically at par values of smaller sized tuber yield during both the years. Similarly smaller sized tuber yield was statistically at par for all the irrigation treatments under M_2 method of planting during the first year.

3.4 Tuber dry weight and Tuber dry yield

The analysis of data for tuber dry weight showed that it did not vary with method of planting. Tuber dry weight was significantly lower for treatment I_5 both under M_1 and M_2 methods of planting methods. Treatment I_3 for first year under M_2 was statistically at par with all the treatments. Tuber dry weight was statistically at par for M_1 and M_2 methods of planting. Tuber dry yield per hectare was higher for ridge-furrow method of planting (M_1) during both the years. Treatment, I_4 recorded highest tuber dry yield both under M_1 and M_2 methods of planting for two years. The tuber dry yield (kg per ha) seemed to be higher under ridge planted crop than that of bed planted crop during both the years. It may be due to significantly higher marketable tuber yield under ridge planted crop as compared to bed plantation. The lowest tuber dry weight per hectare was recorded under I_1 treatment and control treatment for both the years of crop planting. Both of these treatments recorded lower marketable tuber yield during both the years (Table 4).

3.5 Source to sink ratio and root dry weight

The analysis of data for source to sink ratio showed that M_2 method of planting recorded significantly lower source to sink ratio as compared to M_1 in first year. Source to sink ratio seemed to be lower under M_2 method of planting as compared to M_1 in the second year, although these values were statistically at par with each other. Among different irrigation treatments, I_4 in the second year under M_1 and for both the years under M_2 method of planting recorded lowest source to sink ratio. Similarly, treatment I_1 recorded lowest source

to sink ratio under M₁, method of planting during both the years. The source to sink ratio was lower under bed planted tuber crop than that of ridge planted crop during both the years. The lower source to sink ratio implies higher translocation efficiency of canopy to the tubers. Thus, it implies that canopy transferred the photosynthates or nutrients more efficiently under bed-furrow as compared to ridge-furrow method of planting. The data showed that root dry weight did not vary significantly among M₁ and M₂ methods. Among various irrigation treatments, treatment I₅ recorded significantly higher root dry weight for two years both under M₁ and M₂ methods of planting. Treatments, I₂ and I₃ under M₂ recorded statistically at par root dry weight with the I₅ treatment. The higher root dry weight for I₅ treatment may be due to higher water volume utilized for this treatment which probably may have caused higher root growth leading to higher root mass.

3.6 Plant height at 30, 60, 75 DAP and at harvest stage

The analysis of data showed that plant height, recorded at 30 DAP did not vary significantly during both the years. However, the plant height varied with method of planting, it was significantly higher under M₂ as compared to M₁ method of planting during both the years (Table 2). It was observed that plants emerged earlier under bed-furrow plantation (M₂) as compared to ridge-furrow method of planting (M₁). The higher plant height under bed planting method (M₂) may be due to early emergence of tubers as compared to ridge planted (M₁) tubers.

The analysis of data for plant height at 60 & 75 DAP and harvest of crop showed that plant height at all these crop stages were affected both by the methods of planting and irrigation treatments. The plant height at 60 DAP under M₁ was significantly higher as compared to M₂ method of planting during both the years which indicate that plants gained higher growth rate after the crop emergence under ridge-furrow planting method. Significantly higher plant height, at 60 DAP was recorded under I₅ treatment, in the case of both M₁ and M₂ methods of planting during both the years and under I₃ treatment during the second year. Treatment I₅ had received highest amount of irrigation water that may be the reason for faster plant growth and thus achieving higher plant height. Treatment I₃ followed the treatment I₅ in terms of receiving higher amount of irrigation water. Treatment I₄ also recorded significantly higher plant height at 60 DAP under M₂ during both the years and under M₁ in the second year. However, during the first year of planting, plant height in I₄ treatment under M₁ method was statistically at par with the I₃ treatment. In case of plant height gained at 75 DAP and at harvest stage, significantly higher plant height was recorded under M₁ as compared to the M₂, method of planting. Among various irrigation treatments, I₃

and I₄ treatments under M₁ and I₅ under both the planting methods recorded significantly higher plant height at both the crop stages during both the years. However, at both these crop stages under M₂ method, plant height in I₄ was although lower but it was statistically at par with I₅ during both the years. So, the results for plant height indicate that higher plant growth was related to the treatments which had received higher amount of irrigation water leading to sufficient moisture in the root zone for optimum plant growth and development. The plant height was influenced by the interaction of method of planting and irrigation treatments at harvest time during both the years (Table 5 & 6). The higher plant height in ridge planting than that of wide bed planting was also obtained by Qasim et al., (2013).

3.6 Leaf area index and above ground dry matter accumulation at 30, 60 DAP and at harvest stage

Significantly higher leaf area index (LAI) was recorded under M₁ as compared to the M₂ method of planting during the first year of planting. Similarly, LAI under M₁ method of planting during the second year seemed to be higher than M₂, although it was not significantly higher. Among the irrigation treatments, significantly higher LAI was recorded for I₃, I₄ and I₅ treatments under M₁ method of planting during both the years. Under M₂, significantly higher LAI was recorded for I₃ for two years, I₄ and I₅ treatments in the second year. While, treatments I₂ for both years and I₄ and I₅ in first year were statistically at par with above mentioned treatments. The higher LAI for these treatments indicated greater interception of radiation by these treatments, which may probably in turn had caused better partitioning of assimilates to the tubers. The analysis of data showed that the above ground dry matter accumulation (DMA), at 30 DAP was significantly higher under M₂ as compared to M₁ method of planting during both the years. However, at this crop stage above ground DMA did not vary with irrigation treatments. The non-significant differences among the irrigation treatments may be due to nearly equal plant growth for all the treatments at 30 DAP. This may probably due to approximately equal amount of irrigation water received by the various treatment plots at 30 DAP. In case of plant height both at 60 DAP and at the time of harvest, treatments I₅, I₄ and I₃ recorded significantly higher above ground DMA under M₁ method of planting and treatments, I₅ and I₄ under M₂ method of planting during both the years. The treatments I₃ during both the years and I₂ during the second year under M₂ method of planting were statistically at par with the treatments I₅ and I₄. At the harvest stage of crop, significant interaction for above ground DMA between method of planting and irrigation treatments was found during the first year (Table 7). The treatments I₅, I₄ and I₃ received higher amount of

irrigation water compared to other treatments and the increase in above ground dry matter accumulation with increase in irrigation water was also reported by Demlesh (2013).

The advantage of ridge-furrow planting method over bed-furrow planting method in terms of marketable tuber yield, large and medium sized tuber yield and water use efficiency supported the relevance of ridge-furrow planting system over that of bed-furrow planting method. Singh and Sood (2013) also reported that raised bed planting of double and triple row planting of potato is non advantageous as compared to conventional ridge planting under furrow irrigation method.

In conclusion, higher graded and marketable tuber yield and average tuber weight under ridge-furrow planting method was recorded as compared to bed-furrow planting method. About three times higher irrigation water use efficiency was recorded by I₄ treatment as compared to the control (farmers practice) along with saving of 48 to 60% irrigation water. This suggests that irrigation scheduling based on soil matric potential by following ridge-furrow irrigation system is a better criterion in our conditions than that of climatic based irrigation scheduling. Thus, irrigation scheduling by fixing -35 kPa SMP at soil depth of 20 cm from top of the ridge is the best treatment under our conditions.

Conclusion:

Higher plant height, above ground DMA, leaf area index, and graded and marketable tuber yield, tuber dry yield per hectare and water use efficiency under ridge-furrow system was recorded as compared to bed-furrow system. Although higher initial plant growth at 30 DAP and tuber yield for smaller sized tubers and lower blemished percent, source to sink ratio, water volume utilization was observed under the bed planted crop. The advantage of ridge-furrow irrigation system over bed-furrow system in terms of marketable tuber yield and water use efficiency supported the relevance of ridge planting as compared to bed planting. About three times higher water efficiency was recorded by I₄ as compared to control and this treatment showed its upper hand in plant height, above ground DMA, graded and marketable tuber yield and lower discarded percent of tubers under ridge-furrow system among all other treatments. This suggest that scheduling irrigation based on soil matric potential by following ridge-furrow irrigation system is a better criterion in our conditions than that of climatic based irrigation. Thus, irrigation scheduling by fixing -35 kPa SMP at soil depth of 20 cm from top of the ridge is the best treatment under our conditions.

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Table 1: Physical characteristics of soil before planting potato in the year 2012 and 2013

Soil depth (cm)	Bulk density (g cm ⁻³)		Saturated conductivity (cm hr ⁻¹)		Unsaturated conductivity (cm hr ⁻¹)				Infiltration rate (cm hr ⁻¹)	
					Suction I (2cm)		Suction II (4cm)			
Year	2012	2013	2012	2013	2012	2013	2012	2013	2012	2013
0-15	1.36	1.33	310.0	312.0	104.0	106.0	33.0	32.0	7.05	6.85
15-30	1.50	1.48	140.0	145.0	28.0	30.0	10.0	12.0		
30-45	1.63	1.64	144.0	140.0	14.0	13.0	13.0	15.0		
45-60	1.69	1.70	115.0	120.0	23.0	25.0	22.5	24.0		

Table 2: Irrigation water application and water use efficiency during the year 2012 and 2013

Method of planting	Irrigation treatment	Year	Irrigation application (mm)	Total water application ($\text{m}^3 \text{ ha}^{-1}$)	WUE	WUEi
M₁	I₁	2012	235.0	2524.0	0.97b	60.8b
		2013	193.0	2154.0	1.21b	78.1b
	I₂	2012	235.0	2524.0	1.06b	68.7b
		2013	238.0	2604.0	0.98c	65.7c
	I₃	2012	280.0	2974.0	1.04b	68.0b
		2013	286.0	3084.0	0.93c	62.2c
	I₄	2012	235.0	2524.0	1.48a	92.5a
		2013	236.0	2589.0	1.37a	87.2a
	I₅	2012	495.0	5124.0	0.54c	38.8c
		2013	590.0	5524.0	0.43d	32.6d
	Mean	2012	296.0	3132.0	1.02a	65.8a
		2013	308.6	3311.0	0.98a	65.0a
M₂	I₁	2012	210.0	2274.0	1.03b	64.5bc
		2013	213.0	2354.0	1.00b	64.2b
	I₂	2012	250.0	2674.0	0.90b	58.1c
		2013	254.0	2764.0	0.83c	56.3b
	I₃	2012	250.0	2674.0	1.01b	67.7b
		2013	254.0	2764.0	0.91bc	62.3b
	I₄	2012	210.0	2274.0	1.51a	94.4a
		2013	213.0	2354.0	1.30a	85.3a
	I₅	2012	405.0	4224.0	0.61c	42.4d
		2013	450.0	4274.0	0.51d	37.3c
	Mean	2012	265.0	2822.0	1.01a	65.4a
		2013	276.8	2992.0	0.91b	61.1a

Table 3: Vegetative characters as affected by methods of planting and irrigation during the year 2012 and 2013

Method of planting	Irrigation treatment	Year	Pt ht 30DAP (cm)	Pt ht 60DAP (cm)	Pt ht 75DAP (cm)	Pt ht at harvest (cm)	LAI	DMA 30DAP (g)	DMA 60DAP (g)	DMA at harvest (g)	SSR	Root dry weight (g)
M₁	I₁	2012	25.1a	31.1c	32.9b	33.8b	1.80b	8.0a	9.0b	10.5b	0.17b	1.04c
		2013	25.5a	30.1c	32.6b	33.5b	1.62b	8.0a	9.4b	10.4b	0.16c	0.86c
	I₂	2012	24.8a	31.8c	33.0b	34.1b	2.12b	8.2a	9.6b	11.3b	0.18b	1.16c
		2013	25.2a	31.6c	33.3b	34.1b	1.96b	8.3a	10.1b	11.1b	0.17bc	1.13c
	I₃	2012	25.3a	39.1b	44.1a	45.4a	3.12a	8.1a	11.7a	14.4a	0.21a	1.89b
		2013	25.3a	39.5b	44.4a	45.7a	3.18a	8.2a	11.9a	14.1a	0.21a	1.87b
	I₄	2012	25.0a	41.5ab	44.9a	47.8a	3.09a	8.3a	11.9a	14.3a	0.17b	1.12c
		2013	25.6a	42.8a	44.8a	45.8a	3.07a	8.4a	12.6a	13.9a	0.17c	1.16c
	I₅	2012	25.4a	42.6a	45.8a	48.1a	3.56a	8.1a	12.5a	15.3a	0.21a	3.07a
		2013	25.4a	43.2a	45.3a	47.3a	3.21a	8.2a	13.1a	14.3a	0.20ab	3.14a
	Mean	2012	25.1b	37.2a	40.1a	41.8a	2.73a	8.1b	10.9a	13.2a	0.187a	1.66a
		2013	25.4b	37.4a	40.1a	41.3a	2.61a	8.2b	11.4a	12.8a	0.181a	1.63a
M₂	I₁	2012	26.3a	31.1b	33.9c	34.4c	1.69b	9.0a	10.0c	10.6b	0.16ab	0.92c
		2013	26.2a	30.8b	32.3c	32.6c	1.90b	9.1a	10.2b	11.0b	0.17ab	0.93c
	I₂	2012	27.1a	32.1b	34.2c	34.8c	1.90ab	8.9a	10.1bc	11.0ab	0.17a	1.62abc
		2013	27.1a	32.5b	33.3c	33.5c	2.16ab	8.8a	10.7ab	11.4ab	0.18a	1.69ab
	I₃	2012	26.9a	37.1a	39.4b	40.7b	2.35a	9.3a	11.1ab	12.1a	0.18a	1.68ab
		2013	26.5a	37.5a	38.0b	38.2b	2.59a	9.2a	11.4ab	12.5ab	0.19a	1.75ab
	I₄	2012	26.5a	38.7a	42.2ab	42.8ab	2.30ab	9.1a	11.4a	12.0a	0.14b	1.00bc
		2013	27.0a	38.6a	39.5ab	39.5b	2.53a	8.9a	11.7a	12.4ab	0.15b	1.10bc
	I₅	2012	26.7a	39.6a	43.1a	43.8a	2.13ab	9.2a	11.5a	12.0a	0.16ab	2.24a
		2013	26.8a	40.2a	41.7a	43.5a	2.75a	9.3a	11.8a	12.9a	0.18a	2.30a
	Mean	2012	26.7a	35.7b	38.6b	39.3b	2.11b	9.1a	10.8a	11.5b	0.163b	1.49a
		2013	26.7a	35.9b	36.9b	37.4b	2.39a	9.1a	11.2a	12.0b	0.174a	1.55a

* Pt ht= plant height, DAP= Days after planting, LAI= Leaf area index, DMA = Above ground dry matter accumulation and SSR= Source to sink ratio

Table 4: Tuber yield and quality characters as affected by methods of planting and irrigation during the year 2012 and 2013

Method of planting	Irrigation treatment	Year	Average Tuber weight (g)	Marketable Tuber yield (q/ha)	Large Tuber yield (q/ha)	Medium Tuber yield (q/ha)	Small Tuber yield (q/ha)	Smaller Tuber yield (q/ha)	Discarded percent	Green percent	Blemished percent	Tuber Dry Wt (g per 100g)	Tuber Dry Yield (q/ha)
M₁	I₁	2012	30.9b	143.0c	15.1b	24.7d	38.6c	64.5a	4.5b	1.5a	3.0b	17.0a	2904.9
		2013	31.9b	150.7d	14.3c	27.2c	41.1d	68.2a	5.2b	1.8b	3.4b	17.4a	2538.7
	I₂	2012	37.2b	161.4c	18.3b	32.42c	44.7c	65.9a	5.5b	2.1a	3.4b	16.5a	2967.7
		2013	36.3b	156.4cd	17.1c	29.9c	43.8cd	65.7ab	5.0b	2.0b	3.0b	16.4a	2887.7
	I₃	2012	47.1a	190.4b	28.2a	44.5b	54.5b	63.3a	6.2b	2.5a	3.7b	16.2a	3054.8
		2013	47.3a	177.8bc	23.8b	43.6b	49.2bc	61.2b	6.0b	2.4b	3.6b	16.1a	3135.6
	I₄	2012	52.9a	217.3a	31.7a	55.0a	62.5a	68.2a	4.9b	1.9a	3.0b	17.1a	3390.0
		2013	51.6a	206.8a	31.0a	52.3a	59.2a	64.4ab	4.4b	1.6b	2.8b	17.1a	3468.6
	I₅	2012	48.9a	192.2b	28.8a	42.8b	56.1b	64.5a	16.8a	3.1a	13.7a	14.5b	2745.5
		2013	48.6a	183.6ab	25.7ab	40.4b	53.7ab	63.8ab	15.6a	2.9a	12.7a	14.5b	2766.7
	Mean	2012	43.4a	180.8a	24.4a	39.9a	51.3a	66.7a	7.24a	2.14b	5.10a	16.3a	2941.9
		2013	43.1a	175.1a	22.3a	38.6a	49.4a	64.7b	7.58a	2.22b	5.63a	16.3a	2846.4
M₂	I₁	2012	32.0c	135.4c	11.3b	18.3c	40.5c	65.2b	4.5b	2.7ab	1.8b	17.2a	2411.6
		2013	30.6c	136.8b	9.3c	16.3b	41.1c	70.1a	4.7b	3.1b	1.6c	17.2a	2550.0
	I₂	2012	34.2c	145.4c	12.7b	20.8c	45.0c	67.0ab	5.2b	3.0ab	2.3b	16.5a	2629.0
		2013	34.1bc	142.9b	11.4bc	19.4b	43.7bc	65.8a	5.6b	3.4b	2.2bc	16.1a	2674.9
	I₃	2012	43.4b	169.3b	17.3b	30.1b	56.5b	65.4b	5.5b	3.2ab	2.9b	15.9ab	2681.2
		2013	40.9ab	158.2ab	15.2abc	29.7a	48.3b	65.1a	5.2b	3.1b	2.1b	15.9a	2805.6
	I₄	2012	49.5a	198.2a	24.8a	39.1a	63.6a	70.6a	5.1b	2.7ab	2.5b	17.3a	2912.3
		2013	43.8a	181.8a	20.3a	33.7a	58.8a	69.1a	4.8b	2.5b	2.3bc	16.9a	3196.8
	I₅	2012	46.4ab	171.8b	17.6b	32.2b	56.5b	65.5b	18.8a	4.6a	14.2a	15.0b	2595.7
		2013	44.4a	167.8a	17.1ab	29.9a	55.0a	65.8a	17.2a	3.8a	13.4a	14.3b	2625.0
	Mean	2012	41.1a	164.0b	16.7b	28.1b	52.4a	65.3a	7.50a	3.18a	4.32b	16.4a	2684.5
		2013	38.8b	157.5b	14.6b	25.8b	49.4a	67.7a	7.98a	3.24a	4.74b	16.1a	2528.7

* Avg Tr wt= Average tuber weight, Mkt. Tr yield= Marketable tuber yield, Dis. per.= Discarded percent, Gn per.= Green percent, Bd per.= Blemished percent,

Table 5: Interaction table for plant height at harvest during first year

Method of planting	Irrigation levels					
	I ₁	I ₂	I ₃	I ₄	I ₅	Mean
Ridge planting	33.800	34.050	45.400	47.800	48.050	41.820
Bed planting	34.400	34.750	40.650	42.800	43.800	39.280
Mean	34.100	34.400	43.025	45.300	45.925	
				SE _m ± CD	0.373 ± 2.67	

I₁= IW:CPE 1.0, I₂= IW:CPE 1.25, I₃= IW:CPE 1.50, I₄= 20cm×35kPa, I₅ = Control

Table 6: Interaction table for plant height at harvest during second year

Method of planting	Irrigation levels					
	I ₁	I ₂	I ₃	I ₄	I ₅	Mean
Ridge planting	33.500	34.100	45.700	45.800	47.325	41.285
Bed planting	32.625	33.450	38.175	39.500	43.500	37.450
Mean	33.063	33.775	41.938	42.650	45.413	
				SE _m ± CD	0.42 ± 3.19	

I₁= IW:CPE 1.0, I₂= IW:CPE 1.25, I₃= IW:CPE 1.50, I₄= 20cm×35kPa, I₅ = Control

Table 7: Interaction table for above ground dry matter accumulation at harvest for first year

Method of planting	Irrigation levels					
	I ₁	I ₂	I ₃	I ₄	I ₅	Mean
Ridge planting	10.700	11.300	14.400	14.300	15.300	13.200
Bed planting	10.500	10.950	12.100	11.950	12.000	11.500
Mean	10.600	11.125	13.250	13.125	13.650	
				SE _m ± CD	0.257 ± 1.14	

I₁= IW:CPE 1.0, I₂= IW:CPE 1.25, I₃= IW:CPE 1.50, I₄= 20cm×35kPa, I₅ = Control

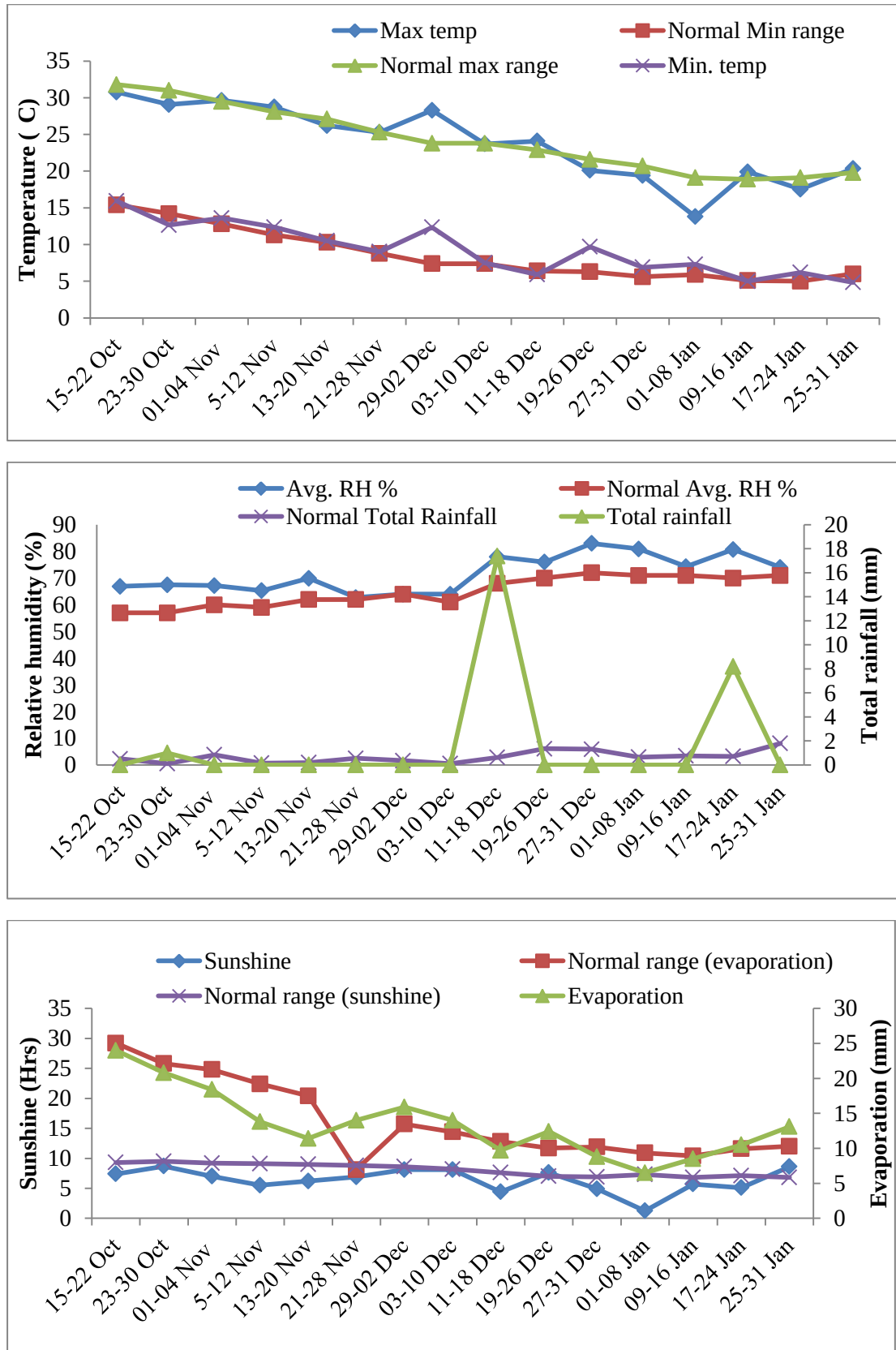


Fig. 1. Maximum and Minimum temperature (°C) (a), average humidity percent and total rainfall (mm) (b), sunshine (Hrs) and Evaporation (mm) (c) during 2012-2013.

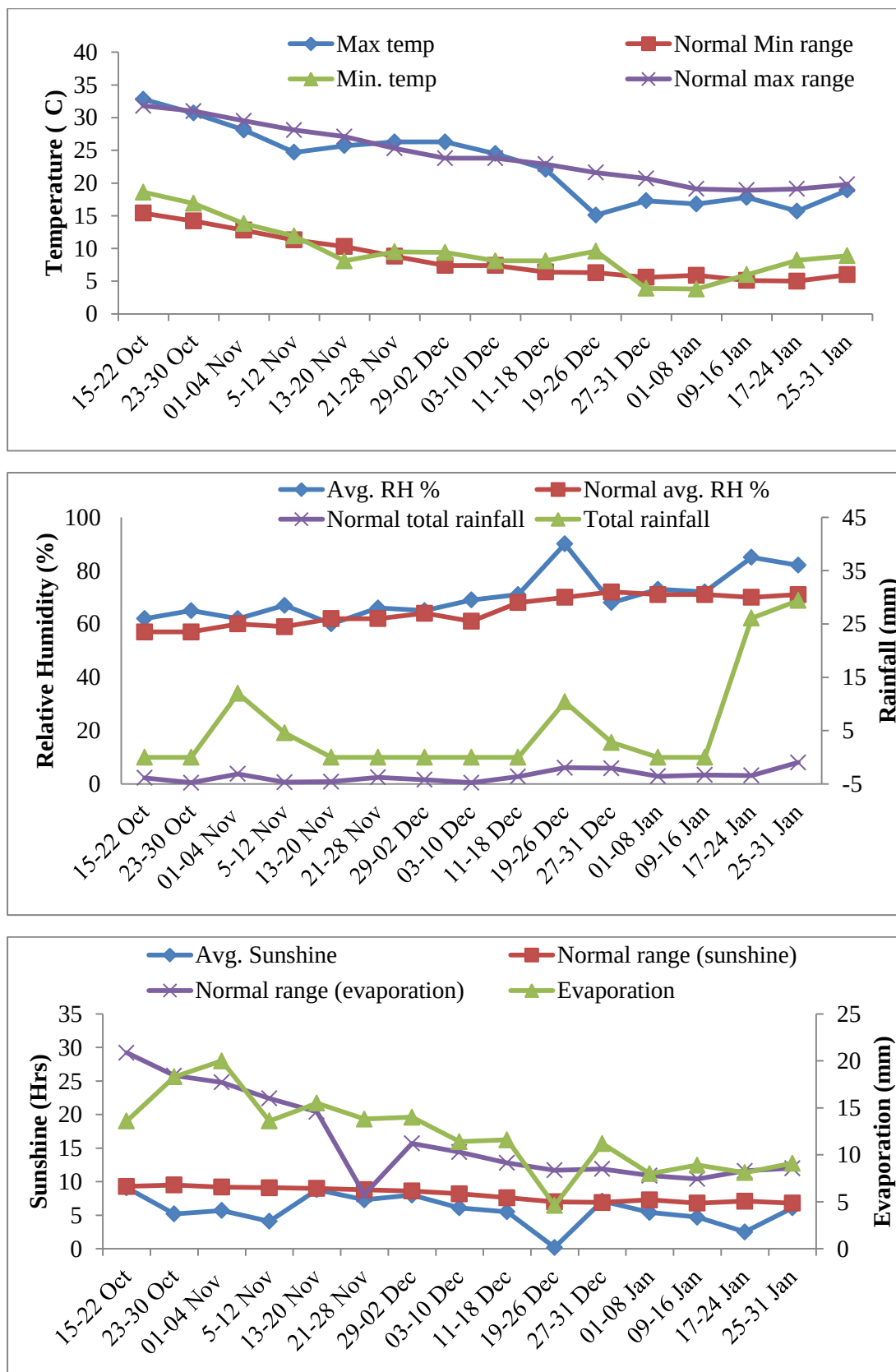


Fig. 2. Maximum and Minimum temperature (°C) (a), average humidity percent and total rainfall (mm) (b), sunshine (Hrs) and Evaporation (mm) (c) during 2013-2014.

EFFECT OF SOIL MATRIC POTENTIAL BASED IRRIGATION SCHEDULING ON YIELD AND QUALITY OF POTATO TUBERS IN THE NORTH-WESTERN INDIAN PLAINS

Sanjeev Ahuja¹, D.S. Khurana² and Kulbir Singh²

ABSTRACT: An Investigation was conducted with the objective to study the effect of irrigation scheduling based on soil matric potential on tuber yield and quality at Vegetable Research Farm, Punjab Agricultural University, Ludhiana during 2011-12 and 2012-13. Three levels of soil matric suction (S); 20, 35 & 50 kPa at three installation depths (D) of tensiometer; 20, 30 & 40 cm and a control (traditional practice) were replicated thrice in RCBD. The analysis of pooled data showed that both S₂₀D₂₀ and S₃₅D₂₀ treatments recorded significantly higher large and medium sized tuber yield. These treatments were also better in terms of recording lower content of reducing sugars and higher percent of starch and protein content. The treatment S₅₀D₄₀ registered highest tuber dry weight during both the years. Treatment S₃₅D₂₀ was better over other treatments in terms of tuber quality, marketable and dry tuber yield in addition to the saving 49% of irrigation water. It also registered more than double WUE as compared to farmers practice (control). Adopting this threshold relates to 3 to 4 irrigations of 45 to 45.5 mm each depending on the rainfall during potato growing period along with two additional irrigations of 50 mm each to substantiate crop emergence.

KEYWORDS: Marketable tuber yield, Potato, Reducing sugars, Tuber dry weight, Water use efficiency

INTRODUCTION

Among the important food crops in the world, potato ranks fourth after Rice, wheat and maize. In India, it is cultivated in different agro-climatic zones with a production of 45 million tonnes from an area of 1.90 million ha. Potato is grown both for ware and processing purpose in this country. The state of Punjab falls in the Indo-Gangetic plains, which is witnessing a high growth rate under potato production. In this state, potato is mainly grown as winter crop in the month of October with an area and production of 85.2 thousand ha and 2.13 million tonne, respectively (Anonymous, 2014). The potatoes are grown chiefly for early lifting and seed tuber purpose in Punjab.

Potato is most frequently irrigated crop and it is known that irrigation consumes maximum energy among all the field operations in potato production (Gulati and Singh, 2011). It requires 7-8 light irrigations under ridge-furrow planting method under North-Western plains of India (Anonymous, 2014). Earlier studies in the region have shown that water is the most important regulating factor for potato production (Kumar *et al.*, 2007; Kumar *et al.*, 2009; Singh *et al.* 2010; Singh *et al.*, 2012). This crop prefers adequate moisture in the root zone owing to its shallow root system as well as for the maintenance of low soil strength, which are conducive for the development and enlargement of tuber. It requires about 400 to 600 mm water for completing its life cycle.

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The ground water resources are being depleted at fast rate in the North-Western plains of India due to excessive utilization for irrigation purpose. The water scarcities have been forecasted in agriculture and non agriculture sectors with changing climate (Hira, 2009). Moreover, there is increased demand of water for organic and non organic agriculture sector, thereby making it necessary to conduct more research on water saving technologies and efficient irrigation schedule on crops.

Insufficient or excessive irrigation can result in reduced yields, reduced specific gravity and increased incidence of tuber defects such as second growth, hollow heart, sclerotium rot, bacterial wilt, verticillium wilt, fusarium wilt, powdery scab and soft rot etc.. It has also been shown that shortage of water may reduce the tuber size (Shock et al., 1998; Cantore et al., 2014).

A large number of scientists have studied the effect of irrigation scheduling on yield and water use efficiency of potato (Panigrahi et al., 2001, Kumar et al., 2009, Singh et al., 2010, Singh et al., 2012, Tyagi et al., 2012, Verma et al., 2013). Moreover, no attention has been paid on the irrigation scheduling based on the criteria of soil matric potential in the previous reported studies. SMP which uses a simple instrument, tensiometer is an easy and reliable technology for irrigation scheduling. Quality is an important aspect of potato tubers from an economic prospective. But a few studies are available about the effect of irrigation scheduling on the quality of potato tubers (Bisht *et al.* 2012; Singh and Sood, 2013). Thus, an investigation with the objectives to study the effect of irrigation scheduling on the quality of tubers in addition to improved tuber yield and water use efficiency was conducted.

MATERIALS AND METHODS:

Site, climate and soil

The details of site, climate and soil are as follows:

Soil Type	Typic Ustipsamment
Location	Vegetable Research Farm, Department of Vegetable Science, Punjab Agricultural University, Ludhiana
Climate	Subtropical and semi-arid
Annual Rainfall	755 mm, mainly concentrated between June to September
Rainfall during potato growing season (October-January)	50-50 mm
Soil texture	Sandy loam
Depth of ground water	Approximately 50 m

Year	2011	2012
pH	7.7	7.9
Electrical conductivity	0.16 dS m ⁻¹	0.24 dS m ⁻¹
Organic C	3.3 g kg ⁻¹	3.5 g kg ⁻¹
0.5M NaHCO ₃ extractable P (Olsen <i>et al.</i> , 1954)	5.75 mg kg ⁻¹	8 mg kg ⁻¹
K (Pratt, 1965)	160 mg kg ⁻¹	172.5 mg kg ⁻¹

Table 1: Physical characteristics of soil before planting potato in the year 2011 and 2012

Soil depth (cm)	Bulk density (g cm ⁻³)		Saturated conductivity (cm hr ⁻¹)		Unsaturated conductivity (cm hr ⁻¹)				Infiltration rate (cm hr ⁻¹)	
					Suction I (2cm)		Suction II (4cm)			
Year	2011	2012	2011	2012	2011	2012	2011	2012	2011	2012
0-15	1.40	1.37	305.0	310.0	103.0	104.0	33.5	33.0	6.93	7.03
15-30	1.55	1.51	136.0	140.0	27.0	28.0	11.0	10.0		
30-45	1.60	1.65	143.0	144.0	15.5	14.0	14.0	13.0		
45-60	1.64	1.72	113.0	115.0	25.0	23.0	24.0	22.5		

Experimental design and crop management

Potato was planted on 18th October and 16th October respectively, during 2011 and 2012. The experiments were laid in randomized complete block design (RCBD) with three replications. Plots with gross plot size, 10.0 m × 5.2 m comprising seven ridges each followed by a furrow, spaced at 60 cm distance were prepared during both the years. Pre-sprouted seed tubers with a mean weight of approximately 45 g were planted 0.2 m apart, on ridges separated from each other by 0.6 m (equivalent to a maintaining a plant density of 8.33 plants m⁻²). Two metre wide border was kept between two adjacent plots as well from irrigation channel to prevent unwanted water seepage. Disease free tubers of an early bulking cultivar, Kufri Pukhraj comprised the plant material. Treatments consisted: S₂₀D₂₀, S₃₅D₂₀, S₅₀D₂₀, S₂₀D₃₀, S₃₅D₃₀, S₅₀D₃₀, S₂₀D₄₀, S₃₅D₄₀, S₅₀D₄₀ and a control (traditional/farmers practice), where ‘S’ is suction/tension level of tensiometers installed at depth ‘D’ in the soil. Dial vacuum gauge tensiometers were installed between two plants and in the centre of the ridge in the middle potato row of each plot. Irrigation was applied only when the soil water tension (SWT) reached its targeted value. Standard crop management practices were followed commonly for each treatment as per the recommendations of PAU package practices for

cultivation. Potato vines were dehaulmed 90 days after planting and tubers were lifted 15 days after dehaulming.

Irrigation treatments:

Pre-plant irrigation measuring 5 cm was given to all plots except control plot. All plots received 5 cm of common irrigation after planting, except control (Farmer's practice) plots which received 11 cm irrigation to facilitate the rooting and establishment of the crop for its complete emergence. After this common irrigation, rest irrigation scheduling was done on the basis of soil matric suction as per the treatment requirement. However, the control treatment received first irrigation 10 days after complete emergence and remaining irrigations at an interval of 12 days (Table 2). An extra irrigation was given to control plots in both years during the days when there were chances of frost occurrence. Thus seven irrigations were applied to the control plots during both the years. Only rainfall exceeding 5 mm within 25 hr was considered effective and included in the calculations for total water use.

Soil matric potential was measured through 18 dial vacuum gauge tensiometers installed one each in a plot in two replications. The average value of targeted SWT was used to schedule irrigation. The observations of targeted SWT value were started on November, 4 in 2011, and November, 11 in 2012. Tensiometers were examined for its proper functioning before installing in the field. One tensiometer per treatment was installed in two replications in the mid of the two plants in the centre of fourth ridge to avoid edge effects. The soil matric potential readings were observed daily between 8.00 a.m. and 9.30 a.m. to minimize the effect of temperature on the tensiometer reading and irrigation was applied thereafter as per the need. However, irrigations in many treatments were delayed when it rained, creating differences between treatments in the total water application in the year, 2012.

Data Collection:

At tuber harvest, 50 plants from each plot were harvested by randomly selecting middle three rows of potatoes; the tubers were picked manually, counted, graded based on the tuber weight and weighed to determine graded, and marketable tuber yield. Malformed, diseased tubers and tubers that weighed <15 g were considered blemished tubers and tubers showing greening disorder were considered as green tubers. Discarded production was determined as percent weight of malformed, diseased, undersized and green tubers of the total tuber yield. Biochemical analysis of fresh tubers was conducted by following standard methods. Total sugars and reducing sugars were determined by the method suggested by Blakeney and Mutton (1980). Starch content was estimated by the method of Westermann *et al.* (1994). Protein content was determined from nitrogen percent which was estimated by Kjeldahl method. Random samples of 100 g tubers were oven-dried at 65°C until constant weight was attained and further weighed to determine tuber dry weight at harvest.

The appraisals for dry tuber yield (kg ha^{-1}) were done by multiplying tuber dry weight per 100g with marketable tuber yield. WUE (kg m^{-3}) was calculated as the ratio of dry tuber yield (kg ha^{-1}) to the amount of water ($\text{m}^3 \text{ha}^{-1}$) applied to the crop (supplemental irrigation plus rainfall) during the potato growing season as per the method suggested by Xie *et al.*(2012). The WUE calculated by this method gives an indication of water productivity.

$$\text{WUE} = \frac{\text{Tuber dry yield}}{\text{Total water applied}}$$

where, total water applied = supplemental irrigation plus rainfall.

Meteorological data

Meteorological data were recorded at meteorological station situated about 500 metre distance from the experimental site. Weekly average temperature, relative humidity, sunshine and total rainfall and evaporation were recorded during the potato growing period from 15th October to 31st January for the year 2011-12 and 2012-13 (Fig.1 & Fig. 2).

Data Analysis

Two years data were subjected to analysis of variance (ANOVA) (Gomez and Gomez, 2010) based on PROC GLM (SAS software 9.1). Pooled analysis of data for two years was also conducted. Duncan's multiple range tests at $p=0.05$ was applied to compare the means of different treatments.

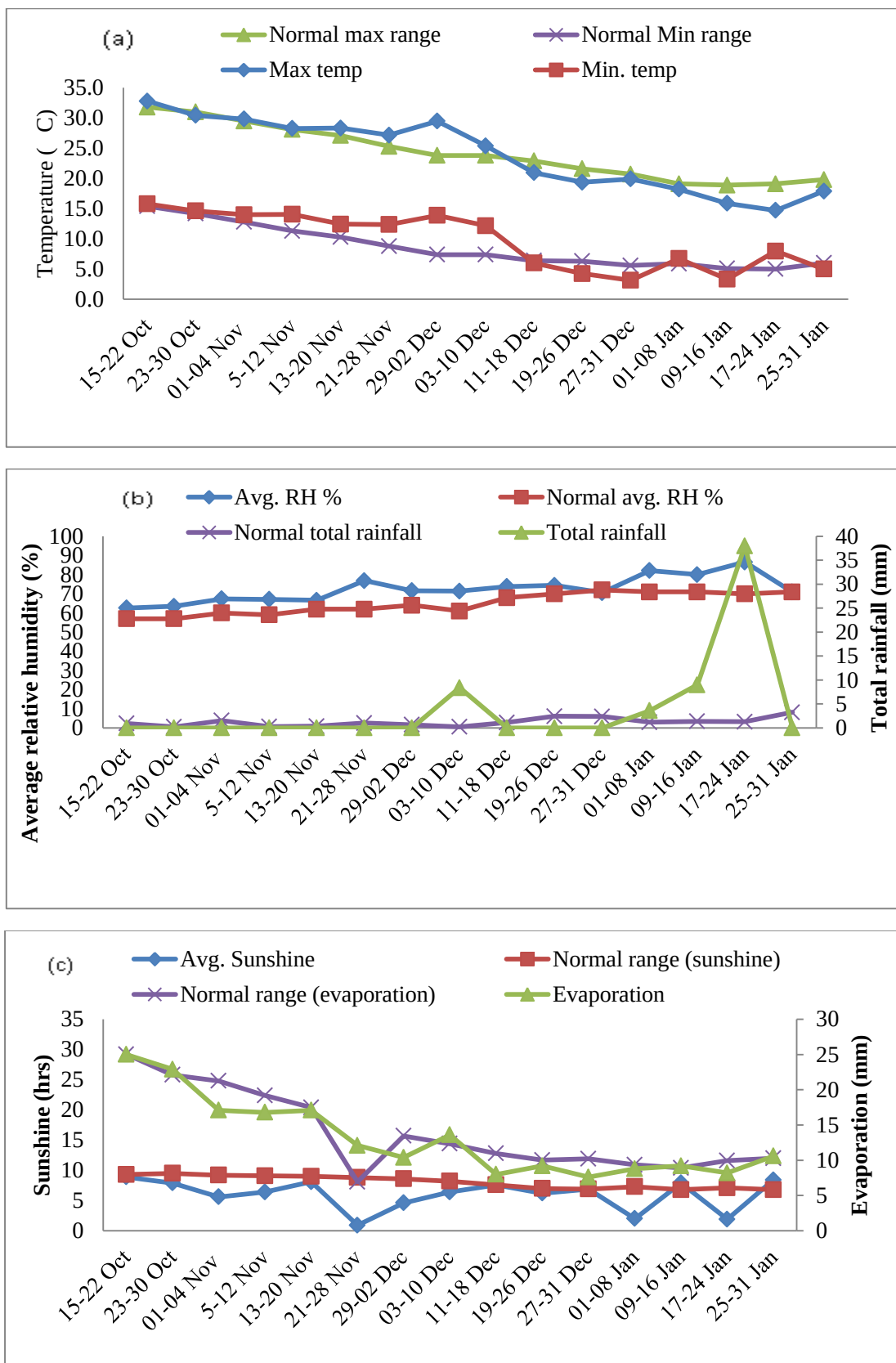


Fig. 1. Maximum and minimum temperature (a), average RH percent & total rainfall (b), average sunshine and total evaporation (c) with their respective average normal range (last 30 years) during the potato growing season 2011-12.

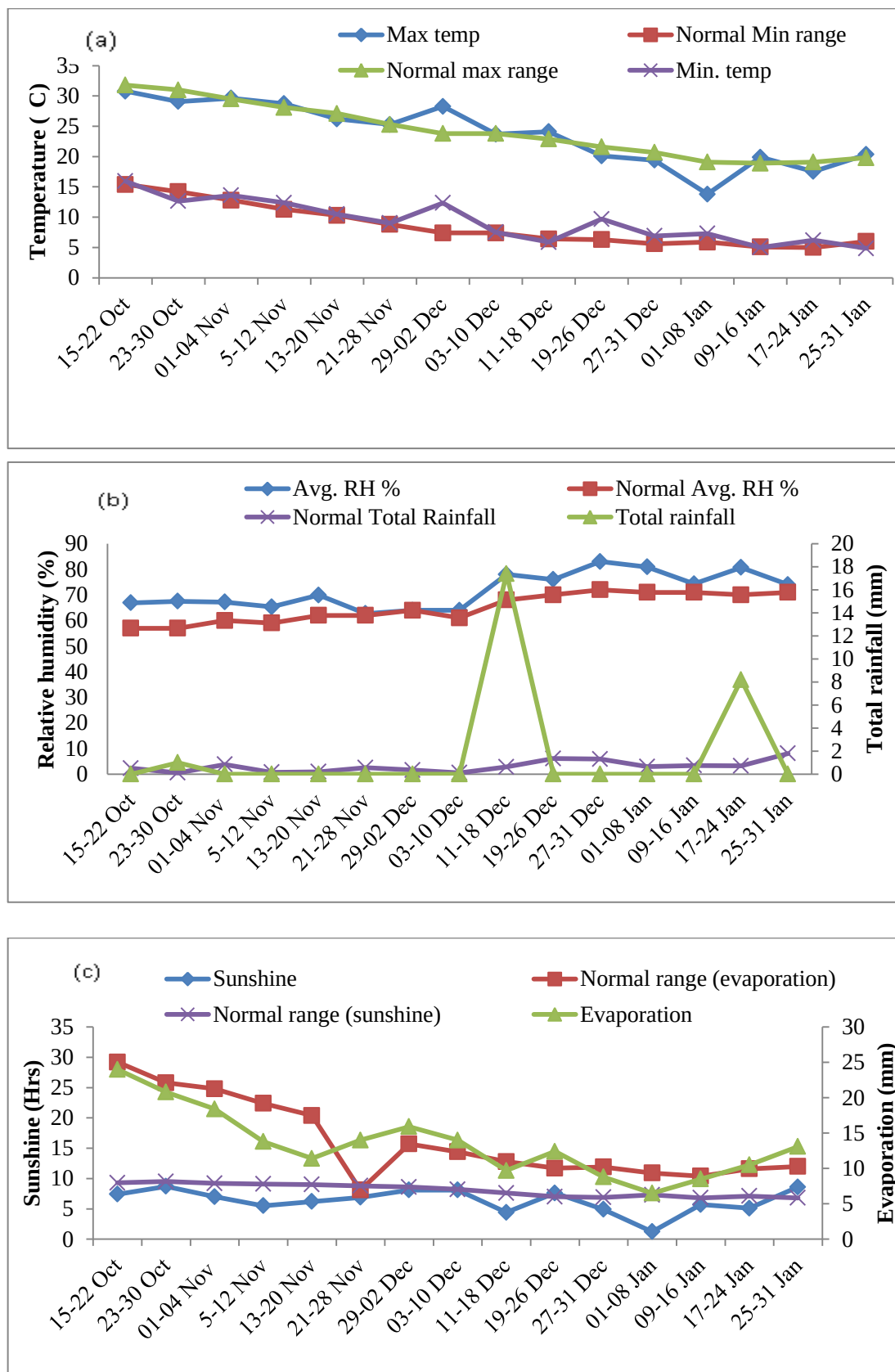


Fig. 2. Maximum and minimum temperature (a), average RH percent & total rainfall (b), average sunshine and total evaporation (c) with their respective average normal range (last 30 years) during the potato growing season 2012-13.

Temperature, rainfall and evaporation

2011-12: As illustrated in Fig. 1 [(a) to (c)], the total rainfall was not uniformly distributed during the period but it was higher during IInd and IIIrd week of January. There were three events of effective rainfall (above 5mm) which summed up to 55.4 mm. The major portion of rain (38 mm) occurred in the IIIrd week of January which was not of much use to the growth and development because potato plants were in late maturity stage and crop was dehaulmed on January 16, 2012. Thus, rainfall of 17.4 mm was considered as effective precipitation for further calculations purpose.

2012-13: During the 2012-13 potato growing period [Fig. 2: (a) to (c)], the total rainfall was not uniformly distributed and was lower than the normal range. There were two events of effective rainfall measuring 17.4 mm and 8.2 mm of water in the IIIrd week of December and IIIrd week of January. But the second event of rainfall occurred after dehauling of potato vines. Thus, only 17.4 mm of rainfall was considered for further calculation purpose.

RESULTS AND DISCUSSION

Irrigation water application

The number and amount of irrigation for different treatments during the potato growing seasons are shown in Table 2. The depth of water for each irrigation event of treatments was constantly changing during the growing season from 45 to 46 mm, the corresponding change was from 57.5 to 60 mm for control. The targeted values of tensiometer recording were started at uniform moisture storage in all the treatments. One major event of effective rainfall during the active growth of crop (December, 2012) disturbed the targeted potentials on the corresponding days, thus less irrigation water was supplied to S₃₅D₂₀, S₅₀D₂₀, S₃₅D₃₀, S₅₀D₃₀, and S₂₀D₄₀ treatments during 2012. The treatment S₅₀D₄₀ received least amount of water during both the years due to lower SMP. Our results are consistent with the findings of Wang *et al.* (2011), they also reported application of lower amount of irrigation water at lower SMP. The control had received highest amount of irrigation water and experienced poor soil aeration, which may ultimately have affected overall plant performance.

Table 2 Number of irrigations, average water application per irrigation, seasonal total irrigation depth, total water application ($\text{m}^3 \text{ha}^{-1}$) and water use efficiency ($\text{kg tuber dry weight m}^{-3}$ of water applied) for different treatments during 2011 and 2012 plantings.

Treatments	Pre-plant irrigation + Crop establishing irrigation	Number of irrigations		Average irrigation application (mm)		Seasonal irrigation application (mm)		Water volume ($\text{m}^3 \text{ha}^{-1}$) (seasonal irrigation application + total rainfall)			WUE ($\text{kg tuber dry weight m}^{-3}$ of water volume)		
Year	2011 & 2012	2011	2012	2011	2012	2011	2012	2011	2012	Average	2011	2012	Pooled
S ₂₀ D ₂₀	50 mm +50 mm	5	5	45.5	45.0	227.5	225.0	3449	3424	3436.5	0.94d	1.04f	0.99c
S ₃₅ D ₂₀	50 mm +50 mm	4	3	45.5	45.0	182.0	135.0	2994	2524	2759.0	1.14abc	1.49bc	1.32abc
S ₅₀ D ₂₀	50 mm +50 mm	3	2	45.0	45.0	135.0	90.0	2524	2074	2299.0	1.23ab	1.60b	1.42ab
S ₂₀ D ₃₀	50 mm +50 mm	4	4	45.0	45.4	180.0	181.6	2974	2990	2982.0	1.06bcd	1.12ef	1.09bc
S ₃₅ D ₃₀	50 mm +50 mm	3	2	45.0	45.0	135.0	90.0	2524	2074	2299.0	1.14abc	1.48bc	1.31abc
S ₅₀ D ₃₀	50 mm +50 mm	2	1	45.0	45.0	90.0	45.0	2074	1624	1849.0	1.30a	1.78a	1.54a
S ₂₀ D ₄₀	50 mm +50 mm	4	3	45.0	45.5	180.0	136.5	2974	2539	2756.5	1.03cd	1.28de	1.15bc
S ₃₅ D ₄₀	50 mm +50 mm	2	2	45.0	46.0	90.0	92.0	2074	2094	2084.0	1.23ab	1.28de	1.25abc
S ₅₀ D ₄₀	50 mm +50 mm	1	1	45.5	45.0	45.5	45.0	1629	1624	1626.5	1.32a	1.39cd	1.36ab
Control	0 +110 mm	7	7	60.0	57.5	420.0	402.5	5474	5299	5386.5	0.46e	0.56g	0.51d
p-value	-	-	-	-	-	-	-	-	-	-	<0.05	<0.05	<0.05

* Column mean with different letters differ significantly at p-value <0.05. ** The effective total rainfall during both the planting seasons was 17.4mm.

Water use efficiency (WUE)

There was an increase in WUE amounting to 186% and 183% in $S_{50}D_{40}$ and $S_{50}D_{30}$, respectively, with a corresponding water saving of 70% and 62% as compared to control during the year 2011 (Table 2). During the year 2012, $S_{50}D_{30}$ increased WUE by 218%, with a water saving of 69% which was followed by $S_{50}D_{20}$ showing 186% increase in WUE along with 61% water saving. The check treatment (control) recorded lowest WUE due to highest amount of water volume consumed by control i.e. 5474 and 5299 $m^3 ha^{-1}$ during first and second year. The WUE in $S_{35}D_{20}$ was upto 177% higher than control when data was pooled over two years. The analysis of pooled data revealed that WUE followed the order of $S_{50}D_{30} > S_{50}D_{20} > S_{50}D_{40} > S_{35}D_{20} > S_{35}D_{30} > S_{35}D_{40} > S_{20}D_{40} > S_{20}D_{30} > S_{20}D_{20} > \text{control}$. The first treatment was significantly higher among all the treatments and next five treatments in the order were statistically at par with each other. Similar trends of higher water use efficiency with the use of lower volume of water were also obtained by Xie *et al.* (2012) in China. Nearly similar range of WUE was obtained by Wang *et al.* (2011) except for the lowest value obtained in our experiment for the control treatment.

Marketable tuber yield

Treatment $S_{20}D_{20}$ produced 6.5% higher marketable tuber yield in 2011 as compared to the year 2012 and the corresponding rate for $S_{35}D_{20}$ was 6.6% (Table 3). Both of these treatments were targeted at lower soil water suction measured in the upper soil layer as compared to the other treatments. The pooled analysis of data showed that treatments $S_{20}D_{20}$ and $S_{35}D_{20}$ recorded 86% and 82% higher marketable tuber yield compared to the control. The marketable tuber yield for control treatment followed these two best treatments. This was in fact reasonable because control treatment had received the highest amount of irrigation water. In $S_{50}D_{40}$ treatment, lowest SWP was measured at 0.4 m soil depth and it had received lowest amount of water volume during both the years. The tuber growth was restrained under this treatment which may probably due to soil moisture deficit in the root zone area. It was seen that potato yield decreased with the drop in SMP from -20 kPa to -50 kPa at all the installation depths of tensiometer. Kang *et al.* (2004) also found that there was continuous decrease in the tuber yield as the soil matric potential increased from -25 kPa to -55 kPa. Our result also agrees with the findings of Wang *et al.* (2007).

The relationship between the average marketable tuber yield (avg. mkt y) and total irrigation water applied (sum of Irrigation water and precipitation = iwp) for different treatments (Fig. 3) is given by the equation Avg. mkt y (q/ha) = 0.187 iwp (mm) + 122.6

Table 3: Tuber dry weight (g per 100 g of fresh weight), Marketable tuber yield (t ha⁻¹) dry tuber yield (kg ha⁻¹), root dry weight per plant (g) and source/sink ratio for potato plantings in the year 2011 and 2012.

Treatment	Tuber dry weight (g per 100 g)			Marketable tuber yield (t ha⁻¹)			Dry tuber yield (kg ha⁻¹)		
Year	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Average
S ₂₀ D ₂₀	15.6cd	16.1bc	15.9cd	20.7a	22.1a	21.4a	3243.9	3556.5	3400.2
S ₃₅ D ₂₀	16.8bc	17.5ab	17.2bc	20.2ab	21.6ab	20.9ab	3402.0	3774.2	3588.1
S ₅₀ D ₂₀	17.7abc	18.2a	18.0ab	17.5cd	18.2de	17.9cd	3112.2	3321.5	3216.9
S ₂₀ D ₃₀	16.8bc	17.5ab	17.2bc	18.7bc	19.1cd	18.9c	3155.1	3344.8	3250.0
S ₃₅ D ₃₀	17.6abc	18.3a	18.0ab	16.3d	16.8ef	16.6de	2879.5	3072.6	2976.1
S ₅₀ D ₃₀	18.2ab	18.8a	18.5ab	14.8e	15.4fg	15.1ef	2695.9	2899.6	2797.8
S ₂₀ D ₄₀	17.0abc	17.7ab	17.4abc	17.9cd	18.4d	18.1cd	3046.1	3259.2	3152.7
S ₃₅ D ₄₀	18.2ab	18.8a	18.5ab	14.0e	14.3g	14.1f	2551.6	2680.9	2616.3
S ₅₀ D ₄₀	19.0a	19.3a	19.1a	11.3f	11.6h	11.5g	2150.6	2252.1	2201.4
Control	14.2d	15.5c	14.9d	18.5c	20.3bc	19.4bc	2539.0	2954.3	2746.7
p-value	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	-	-	-

* Column mean with different letters differ significantly at p-value <0.05.

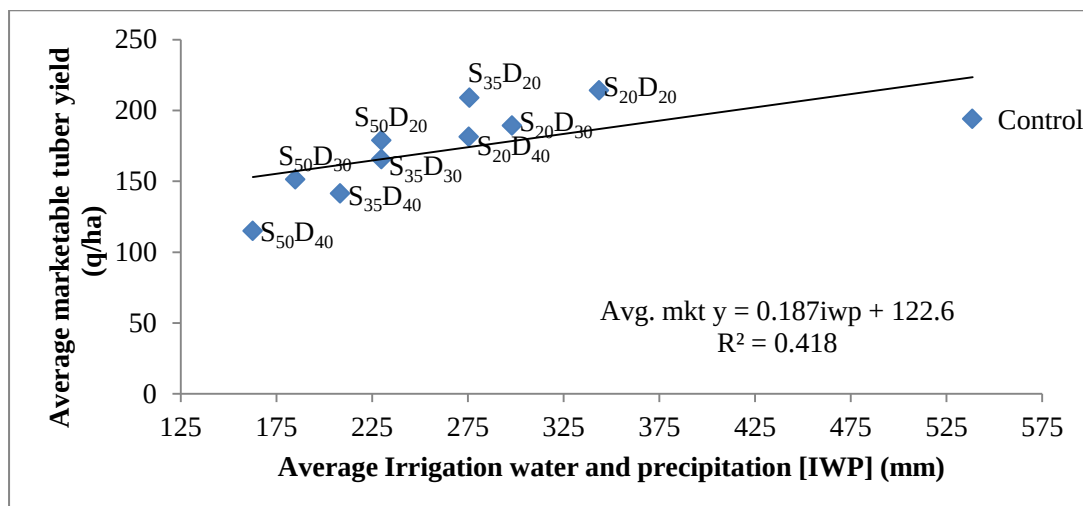


Fig.3. Relationship between marketable tuber yield (average of year 2011 & 2012) and Irrigation water applied (average of year 2011 & 2012) for different treatments.

The value of coefficient of determination between these two variables was found to be 0.418. It was observed that the marketable tuber yield increase with increase in irrigation water application. The relationship between the marketable tuber yield and water use efficiency is shown in Fig. 4. In general, the higher values of water use efficiency correspond to lower marketable tuber yield and *vice versa*. Higher marketable tuber yields and water use efficiency were recorded in S₃₅D₂₀ and S₂₀D₂₀ as compared to the control plot over the two years. The water use efficiency obtained under S₃₅D₂₀ and S₂₀D₂₀ was about double as compared to the control (table 2). Thus, our results suggest that lower SMP of -35 kPa maintained in upper soil depth of 20 cm enhance WUE and maintain tuber yield along with saving of 49% irrigation water.

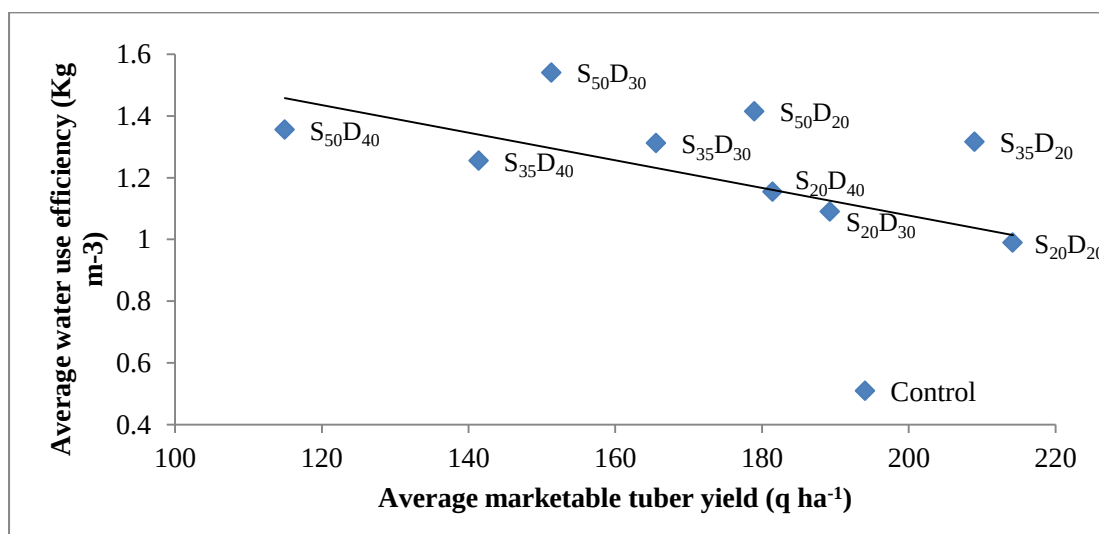


Fig.4. Relationship between marketable tuber yield (average of 2011 & 2012) and water use efficiency (average of 2011 & 2012) for different treatments.

Tuber quality analysis

Significantly higher tuber yield for large sized tubers was recorded for $S_{20}D_{20}$ and $S_{20}D_{20}$ & $S_{35}D_{20}$ (30.1 q/ha in 2011 and 33.4 & 31.5 q/ha in 2012 respectively), which was followed by $S_{35}D_{20}$, control, $S_{20}D_{30}$, $S_{50}D_{20}$ during 2011 and control, $S_{20}D_{40}$, $S_{50}D_{20}$, $S_{20}D_{30}$ treatments during the year 2012 (table 4). Further, analysis of pooled data showed that only control was statistically at par with $S_{20}D_{20}$, $S_{35}D_{20}$ treatments and all other treatments were lower than these treatments. Treatments $S_{35}D_{20}$ during 2011 and $S_{20}D_{20}$ during the year 2012 produced highest medium size tuber yield. The treatments, $S_{20}D_{20}$, control and $S_{20}D_{30}$ in the year 2011 and treatments, $S_{35}D_{20}$, control, and $S_{20}D_{30}$ followed these treatments in 2012. However, when further analysis for pooled data was conducted both $S_{20}D_{20}$ and $S_{35}D_{20}$ were significantly higher than all other treatments and at par with each other. Highest quantity of large and medium size tuber yield for these two treatments might be due to higher overall growth and development of plants owing to lower soil water tension leading to better soil moisture in the root zone area resulting in better size of tubers for these treatments. Irrefutably, higher large and medium size tuber yield under control treatment was in consequence of sufficient soil moisture in the root zone due to maximum quantity of irrigation water received by this treatment. The data indicated that highest small and smaller size tuber yield was produced by $S_{20}D_{20}$ during both the years followed by $S_{35}D_{20}$ treatment. This may be due to higher marketable tuber yields obtained under these treatments. Small size tuber yield followed the order of $S_{20}D_{20} > S_{35}D_{20} > S_{20}D_{30}$ during both the years. The analysis of pooled data for small size tuber yield showed that these treatments were higher and statistically at par with each other. Smaller size tuber yield followed the order of $S_{20}D_{20} > S_{35}D_{20} > S_{20}D_{30} > S_{20}D_{40} \sim \text{control}$ in 2011 and $S_{20}D_{20} > S_{35}D_{20} > \text{control} > S_{20}D_{30} > S_{20}D_{40} > S_{50}D_{20} > S_{35}D_{30}$ in 2012 years. However, treatment $S_{50}D_{40}$ recorded lowest tuber yield for all the four selected grades i.e. large, medium, small and smaller size tubers during both the years which may probably because of continuous lower soil matric potential resulting in lower soil moisture content in the root zone area during crop growth and development period. Similarly, Cantore et al. (2014) recorded maximum percent of undersized tubers in the rainfed treatment.

It was noticed that among all the treatments, green percent of tubers was significantly higher under $S_{50}D_{40}$ during both the years. However treatment $S_{35}D_{30}$ also produced higher green tubers during first year. Further analysis of pooled data showed that $S_{50}D_{40}$, $S_{35}D_{30}$, $S_{50}D_{30}$, and $S_{35}D_{40}$ treatments produced highest percent of green tubers. The tubers under these treatments may have been exposed to sunlight as greening of tubers is related with direct exposure of growing tubers to sunlight. Lowest green percent of tubers was recorded for $S_{35}D_{20}$ during both the years. Significantly higher blemished per cent of tubers was recorded in control during both the years as well as when data was pooled over.

Table 4: Graded tuber yield (t ha⁻¹) and discarded tuber per cent.

Treatment	Graded tuber yield												Discarded production (%)								
	Large			Medium			Small			Smaller			Green % (a)			Blemished % (b)			Discarded % (a+b)		
Year	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Pooled
S ₂₀ D ₂₀	3.01a	3.34a	3.17a	4.90a	5.37a	5.14a	5.83a	6.08a	5.96a	7.00a	7.30a	7.15a	2.80d	2.50c	2.65c	1.41c	3.46b	2.44d	4.21d	5.96bcd	5.09c
S ₃₅ D ₂₀	2.85ab	3.15a	3.00a	5.01a	5.29ab	5.15a	5.64ab	5.97ab	5.81ab	6.73ab	7.16a	6.94ab	2.56d	2.40c	2.48c	2.40b	2.57b	2.49cd	4.96cd	4.97d	4.97c
S ₅₀ D ₂₀	2.15cde	2.30abcd	2.22bc	4.27bc	4.22bcd	4.24bc	5.12abcd	5.40abc	5.26bc	6.01bc	6.33ab	6.17cd	2.90d	2.67bc	2.79c	3.10b	2.67b	2.89bcd	6.00c	5.34cd	5.67bc
S ₂₀ D ₃₀	2.33cd	2.25abcd	2.29bc	4.52ab	4.43abcd	4.47b	5.42abc	5.75ab	5.58ab	6.48ab	6.53ab	6.50abc	2.83d	2.66bc	2.75c	2.58b	3.34b	2.96bcd	5.40c	5.99bcd	5.70bc
S ₃₅ D ₃₀	1.79ef	1.86bcd	1.83cde	3.86cd	3.77cde	3.82cd	4.80cd	4.85bcd	4.83cd	5.88bc	6.30ab	6.09cd	4.60a	4.00ab	4.30a	3.44b	3.10b	3.27bc	8.04b	7.10bc	7.57b
S ₅₀ D ₃₀	1.42fg	1.81bcd	1.61de	3.41de	3.36de	3.39de	4.57de	4.32cde	4.45de	5.44cd	5.93b	5.69d	4.30abc	4.10ab	4.20ab	3.33b	3.40b	3.37b	7.63b	7.50b	7.57b
S ₂₀ D ₄₀	2.03de	2.35abc	2.19bcd	4.18bc	4.28abcd	4.23bc	5.27abcd	5.32abc	5.29bc	6.40ab	6.47ab	6.44bc	3.07bcd	2.59bc	2.83c	2.58b	3.50b	3.04bcd	5.66c	6.09bcd	5.88bc
S ₃₅ D ₄₀	1.32g	1.58cd	1.45ef	3.20e	2.97ef	3.09e	4.02ef	4.06de	4.04ef	5.48cd	5.64bc	5.56d	4.40ab	3.90ab	4.15ab	3.53b	3.54b	3.54b	7.93b	7.44bc	7.69b
S ₅₀ D ₄₀	0.82h	1.07d	0.94f	2.11f	2.17f	2.14f	3.57f	3.57e	3.57f	4.84d	4.84c	4.84e	4.70a	4.30a	4.50a	3.79b	3.70b	3.75b	8.49b	8.00b	8.25b
Control	2.52bc	2.98ab	2.75ab	4.59ab	4.54abc	4.47b	4.99bcd	4.80bcd	5.21bc	6.40ab	6.74ab	6.68abc	3.00cd	3.00abc	3.00bc	11.83a	10.33a	11.08a	14.83a	13.33a	14.08a

* Column mean with different letters differ significantly at p-value <0.05.

All other treatments recorded statistically lower blemished per cent of tubers. Significantly lower blemished percent of tubers was recorded in $S_{20}D_{20}$ during 2011 as well as when the data was pooled over two years. Similar tendency to blemished percent of tubers was also found for discarded tuber percent. Treatments $S_{20}D_{20}$, $S_{35}D_{20}$, $S_{35}D_{20}$, and $S_{35}D_{20}$ recorded significantly lower discarded percent of tubers as shown by the analysis of pooled data. The highest discarded tuber percent was recorded in control (farmer's practice) treatment during both the years which may probably because of higher amount of water application in this treatment leading to excessive soil moisture which in turn amplified tuber deterioration. Qasim et al. (2013) also reported higher green and injured percent of tubers under farmer's practice. Treatment $S_{50}D_{40}$ followed control during both the years which may be due to moisture deficit in the root zone that may had resulted in higher number of malformed tubers during both the years. Thus, both low and high moisture are detrimental for obtaining healthy tubers. Lowest green and blemished percent of tubers were recorded under $S_{35}D_{20}$. Qin et al. (2014) had reported lowest percent of green and blemished tubers under ridge planting in completely mulched wide ridges alternated with narrow ridges under low fertility area at Dingxi, Northwest China. In our experiment also tubers were planted in the ridges in the low fertility area and treatment $S_{35}D_{20}$ may had received optimum soil moisture conditions for growth and development of tubers.

Tuber dry weight and dry tuber yield

The treatment $S_{50}D_{40}$ registered highest tuber dry weight (per 100g of fresh weight) during both the years as well as for pooled data. It was followed by treatments $S_{35}D_{40}$ and $S_{50}D_{30}$ during the same period (Table 3). Minimum tuber dry weight was recorded under control during both the years which may probably be due to higher percent of water present in the tubers in this treatment as compared to other treatments. While, highest tuber dry weight in $S_{50}D_{40}$ indicated presence of lower quantity of water in the tubers. Dry tuber yield was computed from the multiple of tuber dry weight and marketable tuber yield. Dry tuber yield was increased by 34%, 28%, 24%, and 22% in 2011, and 28%, 20%, 13%, and 12% in 2012, respectively, for $S_{35}D_{20}$, $S_{20}D_{20}$, $S_{20}D_{30}$ and $S_{50}D_{20}$. Thus, highest dry tuber yield was recorded for $S_{35}D_{20}$ during both the years.

Thus, maintaining higher SMP in upper soil layer is important as is evident from treatments, $S_{20}D_{20}$ and $S_{35}D_{20}$ (-20 kPa and -35 kPa at 20cm soil depth) which gave higher marketable tuber yield as well as dry tuber yield. These treatments were followed by $S_{20}D_{30}$ treatment which belonged to maintaining SMP of -20 kPa at 30 cm soil depth.

Biochemical properties of tubers

Different treatments affected total sugar content significantly in the first year as well as when data were pooled over the two years (Table 5). However, there was insignificant difference

among the treatments during the second year. The highest sugar content was observed in S₅₀D₄₀ treatment during both the years which had received least amount of irrigation water among all the treatments. The accumulation of higher sugar content in the tubers may probably be due to the conversion of starch into sugars in the soil moisture deficit conditions in the vicinity of root zone. This treatment was followed by S₂₀D₄₀ during first year as well as for pooled data over the two years. The treatments S₃₅D₃₀ and S₂₀D₂₀ were statistically at par with the above mentioned two treatments during the first year. However, reducing sugar content was unaffected by different treatments as non-significant differences among the treatments were observed during both the years. But when data were pooled over two years it was revealed that treatment S₅₀D₄₀ had recorded significantly higher content of reducing sugars. The treatment S₅₀D₃₀ was statistically at par with S₅₀D₄₀. Both of these treatments have received lower amount of water during the life cycle indicating the conversion of starch into reducing sugars because of the activity of sucrose phosphate synthase enzyme probably due to the water stress conditions. However, over results are contrasting to the results obtained by Davies *et al.* (1989), who had reported lowering of reducing sugar content in the tubers due to water stress during crop growth. The lowest amount of reducing sugars was recorded under control, S₂₀D₂₀ and S₃₅D₂₀ treatments. These treatments had received maximum amount of irrigation water resulting in adequate amount of moisture in the root zone which may had caused higher starch deposition without its conversion to reducing sugars. Different irrigation treatments had affected starch and protein contents differentially. It was observed that control treatment had recorded highest amount of starch and protein percent in the tubers followed by S₂₀D₂₀ and S₃₅D₂₀ treatments during both the years. These treatments had received higher amount of irrigation water indicating the sufficient moisture in the root zone which may had probably resulted in the deposition of higher starch and proteins in the tissues. Contrastingly, treatments which had received lower amount of irrigation water had accumulated lower amount of starch and proteins in the tissues, therefore S₅₀D₄₀ recorded lowest amount of starch and protein percent in the tubers due to water stressed conditions in the root zone. Our results for starch content are consistent with the findings of Singh *et al.* (2007) and Ballmer *et al.* (2012) who had also reported reduction in the starch content of tubers under water limitation conditions.

Table 5: Total sugars, reducing sugars, starch percent and protein percent for potato plantings in the year 2011 and 2012.

Treatment	Total sugars (mg)			Reducing sugars (mg)			Starch (%)			Protein (%)		
Year	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Pooled	2011	2012	Pooled
S ₂₀ D ₂₀	801.3abcd	788.7ab	795.0bc	321.7b	313.3bc	317.5cd	15.3a	14.2ab	14.7ab	2.97ab	2.93ab	2.95b
S ₃₅ D ₂₀	791.0bcd	763.0b	777.0bcd	326.7b	318.3abc	322.5cd	14.8ab	13.8bc	14.3bc	2.77bc	2.40bc	2.58bc
S ₅₀ D ₂₀	773.0cd	747.3b	760.2d	328.3b	323.3abc	325.8bcd	14.1cd	12.9d	13.5de	1.80de	1.32de	1.56ef
S ₂₀ D ₃₀	787.0bcd	773.3ab	780.2bcd	333.3b	325.0abc	329.2bcd	14.5bc	13.3cd	13.9cd	2.62bc	2.00cd	2.31cd
S ₃₅ D ₃₀	813.7abc	781.7ab	797.7b	343.3ab	336.7abc	340.0bc	14.1cd	12.7de	13.4e	1.82de	1.47de	1.64ef
S ₅₀ D ₃₀	790.7bcd	748.3b	769.5bcd	350.0ab	348.3ab	349.2ab	12.8f	12.0ef	12.4f	1.88de	1.49de	1.69ef
S ₂₀ D ₄₀	823.0ab	783.3ab	803.2ab	341.7ab	335.0abc	338.3bc	13.5de	12.8de	13.2e	2.22cd	1.83cde	2.02de
S ₃₅ D ₄₀	769.7d	755.7b	762.7cd	340.0ab	326.7abc	333.3bcd	13.4e	12.7de	13.1e	1.65de	1.48de	1.57ef
S ₅₀ D ₄₀	836.3a	824.3a	830.3a	376.7a	355.0a	365.8a	12.6f	11.3f	12.0f	1.37e	1.10e	1.23f
Control	763.7d	743.3b	753.5d	315.0b	301.7c	308.3d	15.1a	14.7a	14.9a	3.48a	3.33a	3.41a
p-value	<0.05	>0.05	<0.05	>0.05	>0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

* Column mean with different letters differ significantly at p-value <0.05.

It was observed that S₃₅D₂₀ registered more than double WUE as compared to farmers practice (control). This treatment was also better over other treatments in terms of tuber quality and yield in addition to the medium saving of irrigation water. Although, highest saving of 70% irrigation water was recorded in the S₅₀D₄₀ treatment followed by S₅₀D₃₀ (66%) as compared to traditional irrigation practice. But, due to continuous soil moisture deficit the tuber yield was drastically reduced in these treatments. Treatment S₃₅D₂₀ utilized 49% less irrigation water as compared to the traditional irrigation practice in the region. The irrigation schedule of this treatment created optimum soil environmental conditions for tuber growth and development through better water and nutrient uptake. Light irrigations for maintaining lower soil moisture tension in upper soil layer (S₃₅D₂₀) was better than the frequent and heavier irrigations as practised by the farmers which lead to reduced WUE. The treatments S₂₀D₂₀ and S₃₅D₂₀ were also better in terms of recording lower content of reducing sugars and higher percent of starch and protein content.

CONCLUSIONS

Our results indicated that the lower soil moisture tension of 35 kPa in the upper 20 cm soil layer (S₃₅D₂₀) has resulted in enhanced tuber growth and development along with saving of irrigation water. This treatment recorded higher marketable tuber yield, WUE along with better tuber quality and biochemical properties among all other treatments tested. Adopting this threshold relates to 3 to 4 irrigations of 45 to 45.5 mm each depending on the rainfall during potato growing period. Two additional irrigations of 50 mm each were applied, first as pre-irrigation and second irrigation to substantiate emergence. Thereafter, the application of single irrigation, two weeks after the complete emergence of crop and remaining 2-3 irrigations at 17 days interval. The soil moisture deficit under all the tested soil depths at higher soil moisture tension of 50 kPa had resulted in poor crop growth and development. Traditional irrigation practice had received highest quantity of water among all the treatments which may have caused more than optimum soil water in the root zone resulting in reduced water and nutrient uptake owing to decreased soil aeration as well tuber health deterioration in this treatment. Soil matric potential irrigation proved to be successful criteria for scheduling irrigation to potato. So, the SMP based irrigation scheduling may further be tested for various cultivars under different agro-climatic conditions in planning for future research.

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CHAPTER IV

GENERAL DISCUSSION

The experiment-I conducted during 2011-12 & 2012-13 supported the following discussions:

1.0 Irrigation water application and soil water tension dynamics

The targeted values of tensiometer recording were started at uniform moisture storage in all the treatments. The reason for same soil moisture storage under different treatments and control is unknown. One major event of rainfall during the active growth of crop (December, 2012) disturbed the targeted SWT, thus less irrigation water was supplied to S₃₅D₂₀, S₅₀D₂₀, S₃₅D₃₀, S₅₀D₃₀, and S₂₀D₄₀ treatments during 2012 which might have increased soil moisture resulting in increased SMP in these treatment plots. The control had received highest amount of irrigation water and experienced poor soil aeration, which may ultimately have affected plant performance and nutrient and water uptake.

Depending upon the treatment, the values of SWT fluctuated in variable range during the cropping period. The soil water tensions for the treatments S₅₀D₂₀, S₅₀D₃₀ and S₅₀D₄₀ showed larger variations compared to the other SWT treatments owing to higher SWT values at different soil depths. These treatments fell to nearly 10 kPa second day after irrigation and often exceeded slightly to their fixed value before irrigation. However, the thresholds for treatments S₂₀D₂₀, S₂₀D₃₀ and S₂₀D₄₀ were often slightly surpassed and were comparatively difficult to maintain due to lower SWT values in the upper soil layer. The possible reason may be time gap between water application and the recovery of soil water tension. The other reason may be higher hydraulic conductivity at higher soil matric potential. Although temporal and spatial distribution of SMP was not measured in our study, but it is assumed that there was lower soil moisture in the effective root zone area.

1.2 Water use efficiency (WUE) and Irrigation water use efficiency (WUE_i)

Treatments S₅₀D₄₀ and S₅₀D₃₀ increased 186% and 183% water use efficiency, with a concomitant water saving of 70% and 62 % than that of control during the year 2011. During the year 2012, S₅₀D₃₀ increased WUE by 218%, with a water saving of 69% followed by S₅₀D₂₀ with corresponding values of 186% and 61%. The check treatment (control) recorded lowest WUE as this treatment had received highest amount of water volume i.e. 5474 and 5299 m³ ha⁻¹ during first and second year. The average value of water use efficiency for two years followed the order of S₅₀D₃₀ > S₅₀D₂₀ > S₅₀D₄₀ > S₃₅D₂₀ > S₃₅D₃₀ > S₃₅D₄₀ > S₂₀D₄₀ > S₂₀D₃₀ > S₂₀D₂₀. Similar trends of higher water use efficiency with the use of lower volume of water were also obtained by Xie *et al.* (2012) in China. Zhao *et al.* (2014) computed the

WUE ($\text{kg ha}^{-1}\text{mm}^{-1}$) based on the dry tuber yield and Ahmadi *et al.* (2014) divided the total tuber fresh weight (kg) by the total applied water (m^3) to calculate water productivity.

The similar trends as for WUE were recorded for WUE_i . Treatments $\text{S}_{50}\text{D}_{30}$ and $\text{S}_{50}\text{D}_{40}$ recorded maximal WUE_i followed by $\text{S}_{35}\text{D}_{20}$ in 2011. In the year 2012, $\text{S}_{50}\text{D}_{30}$ recorded highest WUE_i followed by $\text{S}_{50}\text{D}_{20}$ and $\text{S}_{35}\text{D}_{20}$. Similar to WUE, lowest values of WUE_i were recorded in the control during both the years. $\text{S}_{35}\text{D}_{20}$ recorded 105 and 147% higher WUE_i than that of control treatment in 2011 and 2012. The WUE_i ranged from 34.9 to 78.1 in 2011 and 37.2 to 106.4 in 2012. Approximately similar range of WUE was obtained by Wang *et al.* (2011) except the lowest value obtained for WUE_i in our experiment for the control treatment. The values of WUE obtained by Kang *et al.* (2004) was higher than values of WUE_i obtained in our investigation which may due to less irrigation water consumption in the drip irrigation system. While, the WUE (30.2 to 58.4 $\text{kg ha}^{-1}\text{mm}^{-1}$) obtained by Panigrahi *et al.* (2001) was lower than WUE_i in our experiment because the tuber yield obtained by them was lower than that of ours.

1.3 Marketable tuber yield and average tuber weight

Treatment $\text{S}_{20}\text{D}_{20}$ produced 12 % higher marketable tuber yield in 2011 and 9% in the year 2012 than that of control which was statistically at par with $\text{S}_{35}\text{D}_{20}$ during both the years. Both of these treatments had lower level of soil water suction measured in the upper soil layer as compared to the other treatments.

The tuber yield for control treatment would have been highest if the discarded percent of tubers is ignored. This was in fact reasonable because this treatment had received highest amount of irrigation water. The lowest marketable tuber yield i.e. 83% and 90% lower than $\text{S}_{20}\text{D}_{20}$ in 2011 and 2012, respectively was recorded for $\text{S}_{50}\text{D}_{40}$. In this treatment, lowest SWP was measured at 0.4 m soil depth and it had received lowest amount of water volume during both the years. The tuber growth was restrained in $\text{S}_{50}\text{D}_{40}$ which may probably due to soil moisture deficit in the vicinity of root zone. The result was consistent with Wang *et al.* (2007). Kang *et al.* (2004) also found that there was continuous decrease in the tuber yield as the soil matric potential increased from -25 kPa to -55 kPa. However, the differences between $\text{S}_{50}\text{D}_{20}$ and $\text{S}_{20}\text{D}_{40}$, $\text{S}_{20}\text{D}_{30}$ and $\text{S}_{35}\text{D}_{30}$, control and $\text{S}_{20}\text{D}_{30}$ and $\text{S}_{50}\text{D}_{30}$ and $\text{S}_{35}\text{D}_{40}$ were not significant during both the years. There was decline in the potato yield with drop in SMP from -20 kPa to -50 kPa at all the installation depths of tensiometer (Duncan's test, $P < 0.05$). This decline was 18% and 21% at installation depth of 20 cm, 26% and 24% at 30 cm and 57.7% and 58 % at 40 cm soil depth in 2011 and 2012, respectively.

In terms of average tuber weight, highest average tuber weight was recorded for control which was followed by $\text{S}_{20}\text{D}_{20}$, $\text{S}_{35}\text{D}_{20}$, $\text{S}_{20}\text{D}_{30}$, $\text{S}_{20}\text{D}_{40}$ and $\text{S}_{50}\text{D}_{20}$ treatments during both the years. These treatments were statistically at par with each other. The highest tuber weight

in the control treatment was probably due to sufficient moisture in the root zone which may have resulted in better growth of tubers resulting in large sized tubers. The treatments S₂₀D₃₀, S₂₀D₄₀, S₅₀D₂₀ and S₃₅D₃₀ in the year 2011 and S₂₀D₃₀, S₂₀D₄₀ and S₅₀D₂₀ in 2012 produced statistically similar average tuber weight. Wang *et al.* (2007) also reported higher marketable tuber weight under higher SMP of -25 kPa than that under -45 and -55 kPa.

1.4. Quality Tuber Production

General trend of graded tuber yield was smaller > small > medium > large sized tubers irrespective of the treatments during both the years. The similar trend for graded tuber yield was recorded by Bisht *et al.* (2012) in the North Indian plains. Significantly higher large size tuber yield was recorded for S₂₀D₂₀ and S₂₀D₂₀ & S₃₅D₂₀, which was followed by S₃₅D₂₀, control, S₂₀D₃₀, S₅₀D₂₀ during 2011 and control, S₂₀D₄₀, S₅₀D₂₀, S₂₀D₃₀ treatments during the year 2012. Whereas, treatments S₃₅D₂₀ during 2011 and S₂₀D₂₀ during the year 2012 produced highest medium size tuber yield. The treatments, S₂₀D₂₀, S₂₀D₃₀ and control in the year 2011 and treatments, S₃₅D₂₀, control, and S₂₀D₃₀ followed these treatments in 2012. Highest quantity of large and medium size tuber yield for S₂₀D₂₀ and S₃₅D₂₀ might be due to higher overall growth and development of plants owing to higher soil matric potential leading to better soil moisture in upper soil layer resulting in better size of tubers for these treatments. Noticeably higher quantity of large and medium size tubers in control treatment albeit its highest overall per cent of discarded tubers was due to sufficient soil moisture in the root zone owing to higher quantity of irrigation water received by this treatment. The data indicated that highest small and smaller size tuber yield was produced by S₂₀D₂₀ during both the years followed by S₃₅D₂₀ treatment. This may be due to higher marketable tuber yields obtained under these treatments. Small size tuber yield followed the trend S₂₀D₂₀ > S₃₅D₂₀ > S₂₀D₃₀ during both the years. Smaller size tuber yield followed the trend of S₂₀D₂₀ > S₃₅D₂₀ > S₂₀D₃₀ > S₂₀D₄₀ > control in 2011 and S₂₀D₂₀ > S₃₅D₂₀ > control > S₂₀D₃₀ > S₂₀D₄₀ > S₅₀D₂₀ > S₃₅D₃₀ in 2012 years. However, treatment S₅₀D₄₀ recorded lowest tuber yield for all the four selected grades i.e. large, medium, small and smaller size tubers during both the years which may probably because of continuous lower soil matric potential in the upper soil layer resulting in lower soil moisture content in the root zone area during crop growth and development period. Similarly, Cantore *et al.* (2014) recorded maximum percent of undersized tubers in the rainfed treatment.

The green percent of tubers was significantly higher in S₅₀D₄₀ during both the years. This may be due to higher exposure of tubers to sunlight under lower soil matric potential. Lowest green per cent of tubers was recorded for S₃₅D₂₀ during both the years. Significantly higher blemished per cent of tubers was recorded in control during both the years. The highest discarded tuber percent in control treatment may be due to higher amount of water application

in this treatment leading to excessive soil moisture in turn augmented tuber deterioration. Qasim *et al.* (2013) also reported higher green and injured percent of tubers under farmer's practice. Treatment S₅₀D₄₀ followed control during both the years which may be due to moisture deficit in the root zone as this treatment received minimum irrigation water during both the years. Thus, both low and high moisture may affect tuber quality. Lowest green and blemished percent of tubers were recorded under S₃₅D₂₀, our results are consistent with the findings of Qin *et al.* (2014). They reported lowest percent of green and blemished tubers under ridge planting in completely mulched wide ridges alternated with narrow ridges under low fertility area at Dingxi, Northwest China. This treatment was best in terms of higher dry matter, tuber yields, WUE, output value, and produced tubers with good size.

1.5 Biochemical properties of tubers

However, reducing sugar content was unaffected by different treatments as non-significant differences among the treatments were observed during both the years. The pooled data over two years revealed that treatment S₅₀D₄₀ had recorded significantly higher content of reducing sugars. The treatment S₅₀D₃₀ was statistically at par with S₅₀D₄₀. Both of these treatments have received lower amount of water during the life cycle indicating the conversion of starch into reducing sugars because of the activity of sucrose phosphate synthase enzyme probably due to the water stress conditions. However, our results are contrasting to the results obtained by Davies *et al.* (1989), who had reported lowering of reducing sugar content in the tubers due to water stress during crop growth. The lowest amount of reducing sugars was recorded under control, S₂₀D₂₀ and S₃₅D₂₀ treatments. These treatments had received maximum amount of irrigation water resulting in adequate amount of moisture in the root zone which may have caused higher starch deposition without its conversion to reducing sugars. Different irrigation treatments had affected starch and protein contents differentially. It was observed that control treatment had recorded highest amount of starch and protein percent in the tubers followed by S₂₀D₂₀ and S₃₅D₂₀ treatments during both the years. These treatments had received higher amount of irrigation water indicating the sufficient moisture in the root zone which may have probably resulted in the deposition of higher starch and proteins in the tissues. Contrastingly, treatments which had received lower amount of irrigation water had accumulated lower amount of starch and proteins in the tissues, therefore S₅₀D₄₀ recorded lowest amount of starch and protein percent in the tubers due to water stressed conditions in the root zone. Our results for starch content are consistent with the findings of Singh *et al.* (2007) and Ballmer *et al.* (2012) who had also reported reduction in the starch content of tubers under water limitation conditions.

1.6 Tuber dry weight, Dry tuber yield, Root dry weight and Source to sink ratio

The highest tuber dry weight (per 100g of fresh weight) was recorded for S₅₀D₄₀ during both the years. Treatments S₃₅D₄₀ and S₅₀D₃₀ followed S₅₀D₄₀ during both the years. Treatment control recorded minimum tuber dry weight during both the years which may probably be due to higher per cent of water present in the tubers in this treatment as compared to other treatments and in contrast highest tuber dry weight in S₅₀D₄₀ indicated presence of lower quantity of water in the tubers. Compared to the control treatment dry tuber yield was increased by 34%, 28%, 24%, and 22% in 2011, and 28%, 20%, 13%, and 12% in 2012, respectively, for S₃₅D₂₀, S₂₀D₂₀, S₂₀D₃₀ and S₅₀D₂₀. The tuber dry weight reported by us is higher than the previous studies (Singh *et al.* 2011) conducted in the region. The reason for obtaining higher tuber dry weight may be the error during the investigation or some other unknown cause. The highest root dry weight per plant was recorded for control which was at par with S₂₀D₂₀ and S₃₅D₂₀ treatments and followed by S₂₀D₃₀ treatment during both the years. The higher amount of water volume received by control, S₂₀D₂₀ and S₃₅D₂₀ treatments may probably have resulted in the well developed root system. The higher amount of water volume received by control, S₂₀D₂₀ and S₃₅D₂₀ treatments may probably have resulted in the well developed root system. The treatment S₅₀D₄₀ recorded lowest root dry weight during both the years as it received lowest amount of water volume during both the years. It was reported by Wang *et al.* (2007) that the root weight density declined as the SMP decreased from -35 to -55 kPa.

However, similar root dry weight among full, deficit, and partial root-zone drying irrigation treatments was recorded by Ahmadi *et al.* (2010). Lowest source to sink ratio was recorded for S₃₅D₄₀, S₃₅D₃₀ and S₅₀D₃₀ & for S₅₀D₃₀ and S₃₅D₃₀ which were statistically at par during 2011 & 2012, respectively. Source to sink ratio signifies the translocation efficiency of assimilates from leaves to the tubers and the lowest value indicated the highest translocation of assimilates to the tubers. In contrast, significantly higher source to sink ratio signifies the poor translocation efficiency of assimilates which was recorded for control during both the years. It was observed in general that the treatments which had received lower amount of water volume showed lower values of source to sink ratio as compared to the treatments receiving higher amount of water volume. It may be due to higher translocation efficiency of assimilates to tubers at lower soil moisture content in the root zone. These results obtained for source to sink ratio are contrary to the findings by Ierna and Mauromicale (2012), who had reported lower values of source to sink ratio for the treatments which had received higher amount of water volume. While, non significant differences among different treatments were recorded by Cantore *et al.* (2014) for source to sink ratio.

The higher values of root dry weight per plant and dry tuber yield (kg ha^{-1}) recorded for $S_{20}D_{20}$ and $S_{35}D_{20}$ treatments, point out the need for keeping the top soil (20 cm) moist by maintaining lower SWT. Both of these treatments maintained optimum soil moisture in the root zone area for proper root development and higher nutrient uptake resulting in higher marketable tuber yield and thus higher dry tuber yield. Treatment $S_{20}D_{30}$, which followed the above said treatments for these two assessed variables indicates maintaining lower SWT (20 kPa) in top 30 cm soil depth. Although the root length density was not studied by us, but the inferences from the results may be drawn that major root mass was confined to 30 cm soil depth.

1.7 Growth parameters

Almost similar values of plant height at 30 DAP were recorded for all the treatments during both 2011 and 2012 years, although the plant height during the 2012 was higher as compared to the 2011. Non-significant differences among the treatments 30 DAP during both the years may be due to approximately similar amount of irrigation water received by all the treatment plots during early growing period. Differential irrigation was started only after the emergence of the crop. However, slightly higher plant height was recorded for $S_{20}D_{20}$ during both the years which may be due to lower soil moisture due to irrigation on 23rd and 27th day after planting during first and second year. Plant height at the 60 DAP and at harvest during 2011, was significantly higher for control followed by $S_{20}D_{20}$, $S_{35}D_{20}$ and $S_{20}D_{30}$ treatments, as compared to all other treatments. While, during 2012 significantly higher plant height after 60 DAP and at the time of harvest was recorded for $S_{20}D_{20}$ which was followed by $S_{35}D_{20}$, control and $S_{20}D_{30}$ treatments. The control treatment had received highest amount of irrigation water but smaller plant height was recorded for control in 2012 that may be due to higher secondary branches developed by the plants which are evident from the higher above ground dry weight accumulation under control in the same year (mentioned in the next para). During both the years lowest plant growth was recorded for $S_{50}D_{40}$ at 60 DAP and at the time of harvest. Both of these $S_{20}D_{20}$ and $S_{35}D_{20}$ treatments received irrigation at lowest SWT as compared to all other treatments which might have caused higher plant growth during active growth periods. Higher plant growth at lower SMP was also reported by Wang *et al.* (2011). Higher plant height under control treatment may be due to higher soil moisture as a result of higher amount of irrigation water received by this treatment during both the years.

The tendency of leaf area index (LAI) was same as for plant height at 60 DAP and at the time of harvest. So, plant height increased the LAI in control which was statistically at par with $S_{20}D_{20}$ and $S_{35}D_{20}$ treatments followed by $S_{20}D_{30}$ during both the years. Zhao *et al.* (2014) also reported increase in LAI with the increase in plant height. The control treatment showed expanded LAI due to higher water application. Higher LAI for above mentioned treatments

indicated increased formation of photosynthates owing to higher interception of radiation. It is evident from the assessed variables for growth and yield that these treatments had formation of higher photosynthates resulting in translocation of higher quantity of assimilate towards the tubers. In case of above ground dry matter accumulation 30 DAP, all the treatments during both the years had non-significant differences which may be due to uniform growth in all the treatment plots during early growing period. At 60 DAP, significantly higher above ground dry matter accumulation (DMA) was recorded for control, S₂₀D₂₀, S₃₅D₂₀, S₂₀D₃₀ and S₂₀D₄₀ as compared to all other treatments during the year 2011. During the year 2012, significantly higher above ground DMA at 60 DAP was recorded for control and S₂₀D₂₀ which was followed by S₃₅D₂₀ and S₂₀D₃₀ treatments.

Significantly higher above ground DMA at harvest was recorded both during 2011 and 2012 for control, S₂₀D₂₀ and S₃₅D₂₀ during both the years followed by S₂₀D₃₀ and S₂₀D₄₀ treatments. Lowest above ground DMA was recorded for S₅₀D₄₀ at 60 DAP and at the time of harvest during both the years. Treatments S₂₀D₂₀ and S₃₅D₂₀ recorded 66 % and 59 % higher DMA at harvest as compared to S₅₀D₄₀ during 2011 and these figures were 57 % and 50 %, respectively for the year 2012. The lowest above ground dry matter accumulation in S₅₀D₄₀ might be due to lower soil moisture in the root zone as a result of combination of higher SWT (50 kPa) at more soil depth (40 cm). Higher plant height and above ground DMA was recorded for S₂₀D₂₀, S₃₅D₂₀ and control, as indicated by higher plant growth and development for these treatments. Qin *et al.* (2014) also reported that higher dry matter accumulation is an indicator of higher plant growth.

The results obtained in the experiment, brings out the importance of lower moisture tension in upper soil layer for S₂₀D₂₀ and S₃₅D₂₀ (20 kPa and 35 kPa at 20cm soil depth) treatments which gave higher plant height, above ground dry matter accumulation, leaf area index, higher quantity of good quality graded tuber yield, average tuber weight, marketable tuber yield. These treatments were followed by S₂₀D₃₀ treatment which belonged to SWT of 20 kPa at 30 cm soil depth for all the above mentioned variables.

Nevertheless, the WUE was lower for S₃₅D₂₀ during first year but it helped in better growth and development of the crop. It registered more than double WUE than traditional practice of the area (control). The WUE averaged over two years for S₃₅D₂₀ ranked 4th after S₅₀D₃₀, S₅₀D₂₀ and S₅₀D₄₀ treatments. So based on higher value of WUE, treatment S₃₅D₂₀ qualifies to be the best treatment. This treatment showed edge over other treatments in terms of plant growth, development, tuber quality and yield in addition to the saving of irrigation water. Although, average volume of water used in S₅₀D₄₀ and S₅₀D₃₀ was substantially lower than its usage in S₃₅D₂₀ treatment. Highest saving of 70% irrigation water was recorded in the S₅₀D₄₀ treatment followed by S₅₀D₃₀ (66%) as compared to traditional irrigation practice. But,

plant growth and ultimately the tuber size and tuber yield were drastically reduced in the $S_{50}D_{40}$ and $S_{50}D_{30}$ treatments probably due to continuous soil moisture deficit in the present investigation. The $S_{35}D_{20}$ treatment utilized 49% less irrigation water as compared to the traditional irrigation practice in the region. This might be explained that irrigation schedule of this treatment created optimum soil environmental conditions for tuber and root growth, favouring better water and nutrient uptake. Apparently two reasons may be put forward in the support of keeping lower soil moisture tension of 35 kPa in the upper 20 cm soil layer. The first reason may be the short life cycle of potato crop (in our case it was 90 days for dehaulming and additional 15 days for tuber uprooting) leading to early bulking of crop requiring ready availability of moisture which is essential for maintaining turgidity of leaves and tuber formation and enlargement. Secondly, the potato plant has shallow and sparse root system and about 85% of root mass is confined to the upper 30 cm soil depth (Opena and Porter, 1999, Iwama, 2008). It seems that the dense layer of root mass in the upper soil layer absorbed most of water without allowing it to percolate to the deeper soil layers utilizing it for better nutrient absorption and overall plant growth. When the irrigation was given for maintaining proper soil moisture at soil depth of 40 cm, the presence of lower soil moisture in the top soil layer may have resulted in poor plant growth and lower tuber yield. The better hydraulic conductivity of soil may have allowed the water to percolate down in the deeper layers of soil without its proper use by the roots of potato plant confined mainly in the top soil layer. Delayed irrigation at higher SWT (50 kPa) may have caused lower soil moisture content in the root zone which may have resulted in reduced transpiration and closure of stomata on account of high diffusion pressure deficit in the leaves. Although the evapotranspiration was not studied in the present investigation but higher SWT decline the SMP of the soil thus affecting evapotranspiration of the plants. Light irrigations for maintaining lower soil moisture tension in upper soil layer ($S_{35}D_{20}$) was better than the frequent and heavier irrigations as practised by the farmers which lead to higher discarded production and reduced WUE.

The analysis of growth and yield parameters showed that plant height, LAI, above ground dry matter accumulation, tuber size, tuber dry weight, root dry weight and graded and marketable tuber yield was on higher side during the year 2012 as compared to the year 2011. The difference may be attributed to better sunshine hrs during the planting year of 2012. The sunshine hours were reduced to zero during higher number of days in November, December, 2011 and January, 2012 as compared to the planting season of 2012-13.

The experiment-II was conducted for two potato growing seasons (October to January) in 2012-13 and 2013-14. This experiment supported the following discussions:

1.0 Growth parameters

The plant height varied with method of planting at 30 DAP potato crop, it was significantly higher under bed planting (M_2) than that of ridge-furrow method (M_1) of planting during both the years. The plant height at 60 & 75 DAP and harvest of crop varied both with method of planting and irrigation treatments. The plant height under ridge-furrow method of planting was significantly higher than under bed planting during both the years. The plant height for I_4 and I_5 treatments was higher during 60 & 75 DAP and at harvest than that of all other treatments. However, I_4 was statistically at par with I_3 treatment during 75 DAP and I_5 was highest at the time of harvest during second year planting. The plant height was influenced by the interaction of method of planting and irrigation treatments during 75 DAP & at harvest time. However, plant height was also affected at 60 DAP of crop during second year of planting. The higher plant height in ridge planting than that of wide bed planting was also obtained by Qasim *et al.* (2013).

Significantly higher LAI was recorded under M_1 than that of M_2 during the first year of planting. It seemed higher LAI for ridge planted crop during the second year of planting, although it was not significantly higher than that of bed planted crop. During both the years of investigation significantly higher LAI was recorded for I_3 , I_4 and I_5 treatments than I_1 and I_2 treatments. The higher LAI for these treatments indicated greater interception of radiation by these treatments, which may probably cause better partitioning of assimilates to the tubers.

The above ground dry matter accumulation (DMA) at 30 DAP of crop was higher under bed planted than that of ridge planted potatoes during both the years. The above ground DMA 60 DAP and at harvest of crop was significantly higher as well as statistically par for I_5 , I_4 and I_3 treatments than that of other treatments during both the years. The above ground DMA at harvest was significantly higher under ridge-furrow method of planting than under bed planting. At the harvest stage of crop, method of planting was influenced by irrigation treatments during the first year.

1.1. Average tuber weight (g) and marketable tuber yield (q/ha)

The average tuber weight varied under different methods of planting and irrigation treatments. The higher average tuber weight was recorded under ridge-furrow method of planting than that of bed planting. Singh and Sood (2013) also obtained higher average tuber weight in the traditional ridge-furrow planting as compared to the raised bed planting. The I_4 and I_5 treatments recorded higher average tuber weight than that of all other treatments during both the years. The average tuber weight recorded under ridge planting method of tubers seemed higher than that of bed planted tubers during first year and it was statistically higher during second year of planting. The highest value of average tuber weight was recorded under

I₄ treatment which was statistically at par with control treatment during both the years and I₃ treatment during the second year of planting.

The total marketable tuber yield also varied under different methods of planting and irrigation treatments. The significantly higher tuber yield was recorded under ridge-furrow method of planting than that of bed planting during both the years. It was 10% higher during the first year and 11% higher during the second year in ridge planting than that of bed planting method. The significantly higher marketable tuber yield was recorded under I₄ treatment which was followed by control and I₃ treatment during both the years of planting. During the first year I₄ recorded 14% higher yield than that of control and the corresponding value during the second year was 11%. The lower marketable tuber yield under bed planted crop may be due to moisture stress in the middle of beds, the similar finding of lower tuber yield in the 90 cm wide beds was recorded by Sidhu *et al.* (2005) than that of beds with 60 cm width. In our case also the width of upper surface of bed was 85 cm.

1.2 Tuber quality and Biochemical properties

The large, medium, and smaller size tuber yield varied under different methods of planting and irrigation treatments. The tuber yield was higher under ridge-furrow method of planting than that of bed planting for large and medium size tubers, while reverse was true for smaller size tubers during the second year. Similarly, Singh and Sood (2013) and Singh *et al.* (2010) also recorded higher tuber yield of large sized (>75g) tubers under conventional ridge-furrow system as compared to raised bed planting. In our study, medium size tubers were >75g, thus similar to earlier results were found in our study. There was non-significant difference among methods of planting under small size tuber yield. Among different irrigation treatments, I₄ recorded significantly higher tuber yield under large and medium size tuber yield during both the years and small and smaller size tuber yield during first year. Higher tuber yield was recorded under I₅ and treatments for small and smaller size tuber yield respectively, during second year. The treatment I₁ was statistically at par with I₂ and I₄ treatments for smaller size tuber yield.

The green and blemished per cent of tubers varied with method of planting, the green per cent of tubers was higher under bed planted tubers while, reverse was true for blemished per cent. The higher green percent of tubers may probably due to greater exposure of tubers under bed planted method than that of ridge planted method. The lower blemished percent of tubers in the bed planted crop may be due to lower water volume used than that of ridge planted method which may probably had caused greater tuber malformation and higher diseased tubers. The lowest green per cent of tubers was recorded under I₄ treatment which was statistically at par with other treatments except under control treatment during the first year while the corresponding treatment during second year was I₁ treatment. The per cent

discarded production of tubers varied among different treatments. It was significantly higher for I₅ treatment followed by I₃ & I₂ treatments.

The significantly higher blemished per cent of tubers among all the treatments was recorded under control. The discarded per cent also followed the trend of blemished per cent of tubers for different irrigation treatments. The higher per cent of blemished and discarded tubers under control treatment may probably due to higher water volume used under this treatment which may had caused higher soil moisture near the root zone both for bed and ridge planted tubers. The lowest value of discarded per cent of tubers was recorded under I₁ treatment during second year and I₄ treatment during the first year of planting.

The reducing sugar and total sugar content was not affected by the method of planting and irrigation treatments. However, our results are dissimilar to the findings of Davies *et al.* (1989), who had reported lowering of reducing sugar content in the tubers due to water stress during crop growth. Different irrigation treatments had affected starch and protein contents differentially. It was observed that control treatment had recorded highest amount of starch and protein percent in the tubers followed by I₃ and I₄ treatments under both the methods of planting during both the years. These treatments might had adequate moisture in the root zone which may had probably resulted in the deposition of higher starch and proteins in the tissues. Contrastingly, treatments which had received lower amount of irrigation water had accumulated lower amount of starch and proteins in the tissues. Our results for starch content are consistent with the findings of Singh *et al.* (2007) and Ballmer *et al.* (2012) who had also reported reduction in the starch content of tubers under limited water conditions.

1.3 Tuber dry weight (g per 100g fresh weight), tuber dry weight (q per ha), root dry weight (g per plant), source to sink ratio

The tuber dry weight did not vary with the method of potato planting. The treatment I₅ recorded significantly lower tuber dry weight as compared to other treatments during both the years. The lower dry weight indicates presence of higher moisture in the tubers for this treatment. All other treatments had non-significant differences among themselves during both the years, although it seemed that treatment I₁ and I₄ recorded higher tuber dry weight than that of other treatments. The calculated tuber dry weight (kg per ha) seemed higher under ridge planted crop than that of bed planted crop and treatment I₄ recorded highest tuber dry weight than that of all other irrigation treatments during both the years. It may be due to significantly higher marketable tuber yield under ridge planted crop and similarly for I₄ treatment among all other treatments. The lowest tuber dry weight per hectare was recorded under I₁ treatment and control treatment for both the years of crop planting. Both of these treatments recorded lower marketable tuber yield during both the years.

Although the root dry weight recorded under ridge planted tuber crop was higher as compared to bed planted crop but these values were statistically at par with each other. The root dry weight varied among different irrigation treatments, the I_5 treatment recorded significantly higher root dry weight than that of all other treatments which was followed by I_3 treatment during both the years of planting. The higher root dry weight for I_5 treatment may be due to higher water volume utilized for this treatment which probably may have caused higher root growth and leading to higher root mass. The root dry weight was affected by the interaction among the method of planting and irrigation treatments during the second year of planting. The source to sink ratio was lower under bed planted tuber crop than that of ridge planted crop during both the years. The I_4 treatment recorded lowest source to sink ratio which was statistically at par with I_1 and I_2 treatments during both the years. The lower source to sink ratio implies higher translocation efficiency of canopy to the tubers.

1.4 Water volume (m^3 per ha) utilized and water use efficiency (kg per ha per m^3)

The higher water use efficiency was recorded under ridge planted tubers than that of bed planted tubers during both the years. The significantly higher water use efficiency during the second year of planting was recorded under ridge planted crop than that of bed planted crop. The water use efficiency varied among different treatments, the I_4 treatment recorded highest water use efficiency than that of all other treatments. 189% higher water use efficiency than that of control was recorded by I_4 as 51% water volume was saved during the first year and the corresponding values during the second year were 185% and 53%. The control treatment recorded lowest water use efficiency during both the years of planting. Highest quantity of water volume was utilized by the control treatment during both the years. Approximately 10 % lower water volume was utilized under bed planting than that of ridge planting during both the years.

Singh and Sood (2013) reported that raised bed planting of double and triple row planting of potato is non advantageous as compared to conventional ridge planting under furrow irrigation method.

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CHAPTER V

SUMMARY

Potato is a shallow-rooted and cool-season crop, and its yield is highest when average daytime temperatures are about 21° C. Cool night temperatures are critical for the accumulation of carbohydrates and dry matter in the tubers (Belanger *et al* 2000). Unlike other crops, the economic product here is not exposed to the free atmosphere, but develops inside the soil. In the North-Western India, potato is mainly grown in winter, which receives little rainfall. Moreover, it cannot be sustained on the moisture stored in the soil in the preceding monsoon due to shallow root system. It seems to be most frequently irrigated among the major *rabi* season crops in Punjab. It requires 7-8 light irrigations for higher productivity under Punjab Conditions (Anonymous 2013). However, previous studies in the region have mostly used weather based scheduling, an indirect approach to evaluating soil water availability for the plants and not SWT/soil matric potential for irrigation scheduling to potato (Kumar *et al* 2009, Singh *et al* 2010, Singh *et al* 2012, Tyagi *et al* 2012, Singh and Sood, 2013, Verma *et al* 2013).

Kang *et al* (2004) conducted a field experiment comparing different irrigation frequencies and soil matric potential thresholds on potato. He found that the highest yield and WUE values were achieved with a soil matric potential threshold of -25 kPa and an irrigation frequency of once a day. Wang *et al* (2007) conducted study on the effects of soil matric potential (SMP) on potato growth under drip irrigation in the North China Plain and concluded that an SMP of -25 kPa was most favourable for potato production in terms of potato growth, water use efficiency and I_{WUE} . On reviewing several studies on different crops, Medici *et al* (2014) generalized the statement that irrigated plants should be grown between 10 and 20 kPa SWT to achieve the highest combination of yield and WUE. At the maturity stage, a higher SWT (20–35 kPa) might be advisable to improve fruit quality and WUE without the risk of reducing yield. It was reported by the Medici and his co-workers that there is need for further conducting research on the basis of soil water tension for irrigation scheduling to crops.

Thus a study was being planned during 2011-13 to optimize soil matric potential and climate based irrigation scheduling to potato for efficient use of irrigation water in terms of crop productivity. Therefore, experiment-I was planned for scheduling irrigation based on soil matric potential under furrow-ridge irrigation method under North-Western India with an objective to determine the most appropriate depth for installation of tensiometer and suitable soil matric potential for higher tuber yield and water use efficiency. The experiment-II was planned with the objective to find out the best schedule of irrigation for maximizing water use

efficiency (WUE) under different crop establishment methods in the North-Western plains of India. The study compared climatic based irrigation scheduling with SMP based schedule under furrow-ridge and furrow-bed planting systems.

Area planned for experiments was pre-irrigated before planting tubers except the control plots. Potato was planted on 18th October and 16th October respectively, during 2011 and 2012 in experiment-I. The experiments were conducted in randomized complete block design (RCBD) replicated thrice. Plots measuring 10.0 m × 5.2 m (gross plot size) comprising seven ridges each followed by a furrow, were planted during both the years. Two metre wide border was kept between two adjacent plots as well from irrigation channel to prevent unwanted water seepage. An early bulking cultivar, Kufri Pukhraj comprised the plant material. Pre-sprouted seed tubers with a mean weight of approximately 45 g were planted 0.2 m apart, in rows separated from each other by 0.6 m (equivalent to a maintaining a plant density of 8.33 plants m⁻²). Treatments include: ten treatments involving three levels of soil water tension/suction (20 kPa, 35 kPa, 50 kPa) at three installation depths of tensiometer (20 cm, 30 cm and 40 cm) and a control (traditional practice) thus comprising S₂₀D₂₀, S₃₅D₂₀, S₅₀D₂₀, S₂₀D₃₀, S₃₅D₃₀, S₅₀D₃₀, S₂₀D₄₀, S₃₅D₄₀, S₅₀D₄₀ and a control. Monitoring of tensiometers was started regularly for SMP reading after the complete emergence of the crop. Irrigation was applied only when the soil water tension (SWT) reached its targeted value.

Pre-plant irrigation measuring 5 cm was given to all plots except control plot. All plots received 5 cm of common irrigation after planting, except control plots which received 11 cm irrigation to facilitate the rooting and establishment of the crop for its complete emergence. After this common irrigation, rest irrigation scheduling was done on the basis of soil matric suction as per the treatment requirement. However, the control treatment received first irrigation 10 days after complete emergence and remaining irrigations at an interval of 12 days.

In the experiment-II, The seed tubers (40 to 50 g) of potato were planted on 18th October 2012 and 15th October 2013. The experiments were conducted in split plot design with four replications. There were two main plots comprising ridge-furrow (M₁) and bed-furrow planting (M₂) systems randomized within. Beds with 85 cm top and 120 cm bottom width were prepared each followed by a furrow under bed planting method. Both of ridge-furrow and bed-furrow plots were prepared using semi-automatic potato planter and bed planter respectively. Two rows were planted on each bed. After planting potato crop, 5 cm of common irrigation water was given to ridge-furrow plots and 4 cm to bed plots except control plots which received 11 cm and 9 cm water after planting under ridge-furrow and bed planted plots, respectively for proper establishment of the crop. The treatments consisted of five irrigation levels: I₁; IWCPE (Irrigation water to cumulative pan evaporation) ratio 1.0, I₂;

IWCPE ratio 1.25, I₃; IWCPE ratio 1.5, I₄; 35kPa×20cm (tensiometer installed at 20 cm soil depth maintaining SMP of -35 kPa) and I₅; control (farmers practice in the region). Pre-sprouted tubers were planted at the spacing of 60×20 cm under ridge-furrow and 45×27 cm on the bed (for maintaining equal plant density). All the data were subjected to analysis of variance (ANOVA) (Gomez and Gomez, 2010) based on PROC GLM (SAS software 9.1). Duncan's multiple range tests at p=0.05 was applied to compare the means of different treatments.

In the experiment-I, non-significant differences for plant height among the treatments were recorded at 30 DAP during both the years. During both the years lowest plant growth was recorded for S₅₀D₄₀ at 60 DAP and at the time of harvest. Plant height increased the LAI in control during both the years which was statistically at par with S₂₀D₂₀ and S₃₅D₂₀ treatments followed by S₂₀D₃₀ during both the years. Significantly higher above ground DMA at harvest was recorded both during 2011 and 2012 for control, S₂₀D₂₀ and S₃₅D₂₀ during both the years followed by S₂₀D₃₀ and S₂₀D₄₀ treatments. Lowest above ground DMA was recorded for S₅₀D₄₀ at 60 DAP and at the time of harvest during both the years. The treatments S₅₀D₄₀ and S₅₀D₃₀ increased 186% and 183% water use efficiency, with concomitant water saving of 70% and 62 % than that of control during the year 2011. During the year 2012, S₅₀D₃₀ increased WUE by 218%, with a water saving of 69% followed by S₅₀D₂₀ with corresponding values of 186% and 61%. The similar trends as for WUE were recorded for WUE_i. Treatments S₅₀D₃₀ and S₅₀D₄₀ recorded maximal WUE_i followed by S₃₅D₂₀ in 2011. In the year 2012, S₅₀D₃₀ recorded highest WUE_i followed by S₅₀D₂₀ and S₃₅D₂₀.

Treatment S₂₀D₂₀ produced 12 % higher marketable tuber yield in 2011 and 9% in the year 2012 than that of control which was statistically at par with S₃₅D₂₀ during both the years. In terms of average tuber weight, highest average tuber weight was recorded for control (51.1g and 54.2 g for 2011 and 2012) which was followed by S₂₀D₂₀, S₃₅D₂₀ treatments during both the years. These treatments were statistically at par with each other. General trend of graded tuber yield was smaller > small > medium > large sized tubers irrespective of the treatments during both the years. The treatments S₃₅D₂₀ during 2011 and S₂₀D₂₀ during the year 2012 produced highest medium size tuber yield. The treatments, S₂₀D₂₀, S₂₀D₃₀ and control in the year 2011 and treatments, S₃₅D₂₀, control, and S₂₀D₃₀ followed these treatments in 2012. However, treatment S₅₀D₄₀ recorded lowest tuber yield for all the four selected grades i.e. large, medium, small and smaller size tubers during both the years. The highest tuber dry weight (per 100g of fresh weight) was recorded for S₅₀D₄₀ during both the years. Treatments S₃₅D₄₀ and S₅₀D₃₀ followed S₅₀D₄₀ during both the years. Treatment control recorded minimum tuber dry weight during both the years. Compared to the control treatment dry tuber yield was

increased by 34%, 28%, 24%, and 22% in 2011, and 28%, 20%, 13%, and 12% in 2012, respectively, for $S_{35}D_{20}$, $S_{20}D_{20}$, $S_{20}D_{30}$ and $S_{50}D_{20}$.

The treatment $S_{50}D_{40}$ recorded lowest root dry weight during both the years. The higher values of root dry weight per plant and dry tuber yield (kg ha^{-1}) recorded for $S_{20}D_{20}$ and $S_{35}D_{20}$ treatments. Lowest source to sink ratio was recorded for $S_{35}D_{40}$, $S_{35}D_{30}$ and $S_{50}D_{30}$ & for $S_{50}D_{30}$ and $S_{35}D_{30}$ which were statistically at par during 2011 & 2012, respectively.

In the experiment-II, significantly higher plant height was recorded by I_5 treatment both under M_1 and M_2 during both the years and by I_3 treatment during second year. Treatment I_4 also recorded significantly higher plant height under M_2 during both the years and under M_1 in the second year. However, during the first year of planting, plant height in I_4 treatment under M_1 method was statistically at par with the I_3 treatment. Significantly higher plant height at 75 DAP and at harvest was recorded for I_3 and I_4 treatments under M_1 and I_5 under both the planting methods during both the years. However, at both these crop stages under M_2 method, plant height in I_4 was although lower but it was statistically at par with I_5 during both the years. Significantly higher leaf area index (LAI) was recorded under M_1 as compared to the M_2 method of planting during the first year of planting. Similarly, LAI under M_1 during the second year of planting seemed to be higher than M_2 , although it was not significantly higher. Among the irrigation treatments, significantly higher LAI was recorded for I_3 , I_4 and I_5 treatments under M_1 method of planting during both the years. Under M_2 , significantly higher LAI was recorded for I_3 for two years, I_4 and I_5 treatments in the second year. While, treatments I_2 for both years and I_4 and I_5 in first year were statistically at par with above mentioned treatments. The above ground dry matter accumulation (DMA) at 30 DAP was significantly higher under M_2 as compared to M_1 method of planting during both the years. However, at this crop stage above ground DMA did not vary with irrigation treatments. In case of above ground DMA both at 60 DAP and at the time of harvest, treatments I_5 , I_4 and I_3 recorded significantly higher above ground DMA under M_1 method of planting and treatments, I_5 and I_4 under M_2 method of planting during both the years. The treatments I_3 during both the years and I_2 during the second year under M_2 method of planting were statistically at par with the treatments I_5 and I_4 .

Average tuber weight under M_1 was significantly higher during second year. It was significantly higher for I_3 , I_4 and I_5 under M_1 and for I_4 under M_2 during both the years and for I_5 under M_2 during second year. Marketable tuber yield was significantly higher for I_4 under M_1 and M_2 during both the years and I_5 under M_2 during second year. Marketable yield for I_5 under M_1 during second year was higher and statistically at par with I_3 during both the years. Similarly, marketable tuber yield for I_5 under M_2 during second year was also significantly

higher compared to I₁, I₂ and I₃ treatment although I₃ treatment was statistically at par with higher marketable tuber yield during second year.

Among the two methods, M₁ recorded significantly higher tuber yield for large and medium sized tubers during both the years. While, during the second year, M₂ showed significantly higher tuber yield for smaller sized tubers. Among different irrigation treatments, I₃ and I₅ for first year, and I₄ during both the years under M₁ recorded significantly higher large sized tuber yield. Under M₂, I₄ recorded significantly higher large sized tuber yield and I₃ and I₅ for second year registered statistically at par tuber yield with I₄. I₄ treatment recorded significantly higher medium and small sized tuber yield both under M₁ and M₂ during two year. Medium sized tubers yield for I₃ during second year under M₂ was also significantly higher. Among the two methods discarded percent did not vary while green percent was significantly higher under M₁ and it was M₂ for blemished percent during two years. Among different irrigation treatments, discarded percent was significantly higher in I₅ under M₁ and M₂ during both the years. Blemished percent of tubers followed the trend shown by discarded percent. While, green percent of tubers was significantly higher in I₅ for two year and I₁, I₂, I₃ and I₄ in the first year under M₁. Similarly, I₅ showed significantly higher green percent under M₂ for two years and I₂, I₃ and I₄ treatments were statistically at par with I₅ treatments.

Tuber dry weight was significantly lower in I₅ both under M₁ and M₂. Tuber dry yield per hectare was higher for M₁ during both the years. I₄ recorded highest tuber dry yield both under M₁ and M₂ for two years. Root dry weight did not vary significantly among M₁ and M₂ methods. Treatment I₅ recorded significantly higher root dry weight for two years under M₁ and M₂ methods. Treatment I₂ and I₃ under M₂ recoded statistically at par root dry weight with I₅. M₂ recorded significantly lower source to sink ratio as compared to M₁ in first year. While, M₂ was lower as compared to M₁ in second year although these values were statistically at par with each other. Among different irrigation treatment, I₁ and I₄ in second year recorded lowest source to sink ratio under M₁. The corresponding values under M₂ were I₄ for both the years. M₂ recoded significantly higher water use efficiency as compared to M₁ in the second year. Among all the irrigation treatments, I₄ recorded significantly higher water use efficiency under M₁ and M₂ during both the years. However, the biochemical quality variables such as reducing sugar and total sugars were not affected by method of planting and irrigation treatments. The starch and protein percent was higher under control, I₃ and I₄ treatments under both the methods of planting and during both the years.

Our results indicated that the lower soil moisture tension of 35 kPa in the upper 20 cm soil layer (S₃₅D₂₀) has more than doubled the water use efficiency as compared to the controlled as 49 per cent irrigation water is saved under ridge-furrow planting method.

Adopting this threshold corresponds to 3 to 4 irrigations of 45 to 45.5 mm each depending on the rainfall during potato growing period. Two separate irrigations of 50 mm each were applied, first as pre-irrigation and second irrigation to substantiate emergence. Thus, application of single irrigation two weeks after the complete emergence of crop and remaining 2-3 irrigations at 17 days interval may save irrigation water as compared to the traditional irrigation practice.

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