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GROWTH AND YIELD RESPONSES OF POTATO (*SOLANUM TUBEROSUM* L.) TO BIOCHAR

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ABSTRACT. The response of five types of biochar (*Lantana camara*, *Ipomoea carnea*, rice husk, sawdust, no biochar) on growth and yield attributes of potato was evaluated. The experiment was laid out in randomized complete block design with six replications in rainfed areas of two different environments (Jiri in 2018 and Pawati in 2019) of Nepal. The popular early maturing potato variety 'Desiree' was used in the experiment. The spacing was maintained 60 cm between rows and 25 cm between plants in the plot size of 7.2 m^2. Seed tubers were planted in the 1st week of February and harvested in the 4th week of May. Recommended fertilizers (100:100:60 kg ha^{-1} NPK + 20 t ha^{-1} farmyard manure) and biochars at 2 t ha^{-1} were applied to the soil. Seed tubers were completely covered with an equal amount of biochar before covering with the soil. The results revealed that the total yield and marketable yield of potato varied with biochars types. The potato tuber yield was found higher and red ants infestation was lower in plots applied with biochars as compared to control plots (without biochars). The use of biochars derived from *Lantana camera* produced the highest number of tubers (6.1 tubers plant^{-1}), the greatest weight of tubers (286.1 g plant^{-1}) and the least damage of red ants on tubers (4.7%) followed by sawdust (6.0 tubers plant^{-1}, 263.6 g tuber weight plant^{-1} and 7.8% damaged tubers by red ants). The findings provide new information on the understanding of biochar effect on increased marketable yield of potato in rainfed lands by reducing damage from red ants.

Introduction

Potato (*Solanum tuberosum* L.) is one of the most important parts of the vegetable recipe of Nepalese cuisine throughout the country and a staple food source for the residents of high hills and mountains. It is commercial non-cereal produce of Nepal and an important source of income for the farmers. However, its productivity is low (14.7 t ha^{-1}) in the country (MoALD, 2019). This low productivity of potato in Nepal is constrained by various factors. The factors identified by National Potato Research Program (NPRP) were low yielding varieties, inadequate cultivation practices with the soil-cultivars-climate complex, inadequate control measures for major diseases and insect pests, insufficient soil fertility management practices (NPRP, 2015). Specifically, drought, red ants, post-harvest losses due to insect pests and diseases and poor performance of varieties in specific microclimate are some of the major threats in country's potato industry (NPRP, 2019).

To reduce the productivity of potato, red ants (*Dorylus orientalis* Westwood) play an important role in causing damage to the potato tubers. Red ants are the most destructive insect pests of potato in the field (Sharma *et al*., 2019). Previous studies showed that the pest could cause 15 to 82% tuber damage in potato fields (Joshi, 1998; Bhandari, 2011). About 35 to 90% damage of potato tubers by this pest was reported in India and Bangladesh (Mishra *et al*., 1993; Konar *et al*., 2005; Alam, 2012). Entomology Research Division of NARC has recommended applying resistant varieties but no variety is perfectly resistant (no damage) yet, however, there were some less damaged clones (Sharma *et al.*, 2017). Earlier studies had identified some local cultivars such as Sabet local, Chisapani Rato and Khumbule as less damaged by red ants in Lumle, Bhitri, and Kabre (Dolakha) in Nepal (Joshi, 1998). However, these cultivars are very old and degenerated now and need to be validated for their performance. In a separate experiment, varietal resistance of potato against red ant was studied in Nepal by Sharma *et al.* (2015) and showed that the potato genotypes CIP 385499.11, CIP 393077.54, PRP 056267.9, PRP 056267.1, CIP 395112.32, and PRP 016567.12 were found the least damaged types but none of them was released.

Similarly, lack of irrigation is a major problem in potato producing upland areas of the hills. Reduction of carbon through reduced application and replenishment of organic matter is also prevalent in these areas (Tripathi, 2015). In the hills, many soils are acidic by nature due to various reasons (Vista, Adhikari, 2015). Potato producing areas of Dolakha districts such as Jiri and Pawati are also in such categories. Considering this fact, the possibility of application of biochar was considered as a researchable issue by NPRP in 2016.

Biochar is a black carbon manufactured through pyrolysis of biomass (Lehmann *et al*., 2006; Upadhyay, 2015). It is effective for improvement of cation exchange capacity, the durability of soil aggregates, microbial activity, bioenergy production and water retention capacity; reduction of nitrous oxide and methane emissions from soils, leaching, soil erosion and need of fertilization and thereby enhancement of soil fertility and crop yields (Brandstaka *et al.,* 2010; Upadhyay, 2015) and adsorption of anions and cations to prevent leaching of applied nutrients (Major *et al*., 2009, Upadhyay, 2015). Biochars may also have some pesticidal activity with potential for the formulation of biopesticides (Sayed *et al*., 2018), for example, lower concentrations (≤1%) of biochar often suppress several diseases (Frenkel *et al*., 2017). Yet, the longevity of the biochar effect on disease severity is unknown (Graber *et al*., 2014)

In recent years, biochar effects are concerned with their economic value. In Australian condition, biochar mixed with NPK increased 53% crop yield led into an increase in farmer net benefits by the US $8 000 per hectare, at a biochar cost of US $160 per hectare (Robb, Joseph, 2019). In an estimate conducted in Canada, biochar application did not cover average total costs for potatoes showing average annualized net returns of US $965.48 ha^{-1} over variable costs (Keske *et al.*, 2019). In another estimate done in Canada, potato production yields average annualized net returns of US $965.48 ha^{-1} over variable costs. In a recent study (Farooque *et al.*, 2020), the maximum net benefit (US $4 433.98 ha^{-1}) was achieved by the combination of the recommended dose of fertilizer and biochar in comparison with control treatment that had a net loss of US $–2621.49 ha^{-1} in Canada. To know the further benefits from the commercialization of biochar, a comprehensive market study is required.

In Nepal, little works have been undertaken to test the biochar on soil fertility and crop growth but the outstanding results are yet to be explored. Vista *et al*. (2015) suggested its potentiality in Nepalese agriculture after gaining farmers' positive response when it was tested in potato, maize, onion, sugarcane, zinger, barley and tomato. Rice husk biochar was effective for the growth and development of garden pea (Bhattarai *et al*., 2015). However, the studies on the influence of on yield, biotic and abiotic stresses are inadequate. Therefore, the present experiment was conducted to assess the effectiveness of biochar on yield response and red ant infestation in potato cultivar 'Desiree' in two ecological conditions of Dolakha district in 2018 and 2019. The present study aimed to assess the efficacy of biochar to improve potato yields in rain-fed uplands where soil moisture was inadequate for crop growth. The other objective of the study was to evaluate the biochars against red ants to reduce yield loss by the insect pest.

Materials and methods

Site description

An experiment was conducted at Jiri and Pawati villages of Dolakha district in 2018 and 2019, respectively. Jiri village was situated at 27°38'0" N and 86°14"0' E with an altitude of 1 900–2 500 meters above mean sea level while the experimental site was in 1950 masl. Its climate was a temperate type where a crop of potato could be grown in a year during spring-summer. The cultivable lands were uplands, rain-fed and dry where winter frost provided moisture for germination of potato tubers. Similarly, Pawati village was situated near Tamakoshi river, 40 km west from Jiri. The altitude of Pawati was 1 200–1 500 meters above mean sea level with a subtropical climate and upland terraces where two crops of potato could be grown in a year during October–January and March–June. The monthly average maximum temperatures were 16, 18, 22, 33, 28 and 28 °C and minimum temperatures were 7, 9, 11, 15, 18 and 23 °C from January to June in 2019, respectively (HCRP, 2020 Fig. 1). In 2018, the monthly average maximum temperatures were 19.3, 24.3, 24.5, 26.5, 28.5 and 28.8 °C and minimum temperatures were 5.5, 7, 9.3, 12.5, 13.3 and 13.0 °C in the same months. Monthly total rainfall was 3, 7, 5. 10, 80 and 60 mm in 2019 whereas it was 6.2, 3, 32, 36, 180.3 and 181.2 mm in 2018 during the same months, respectively. The soils of Jiri and Pawati were characterized by the acidic, well-drained sandy loam in texture based on the World Reference Base for Soil Resources (FAO, 2014). The soil pH of Jiri and Pawati ranged 5.0–5.4 and 4.8–5.2, respectively.

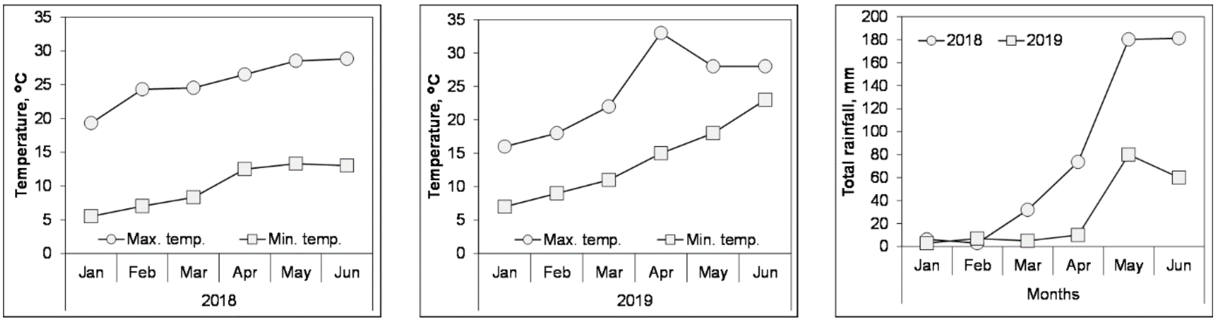

Figure 1. Monthly average temperatures and rainfall during cropping season at Kabre, Dolakha

Preparation of biochar

Biochar produced from *Lantana camara*, *Ipomoea carnea* var. *fistulosa*, rice husk and sawdust were used for the experiment. Plant materials of Lantana and Ipomoea were collected from wastelands and dried under the sun for 15 days. Wood dust was received from a sawmill, whereas rice husk was obtained from a rice mill in Lalitpur district. These materials were pyrolysed in a Kon-Tiki Flame Curtain kiln prepared by Soil Science Division of NARC according to the design recommended in previous reports (Schimidt *et al*., 2015; Cornelissen *et al*., 2016). The temperature in the main pyrolysis zone of the kiln ranged 680–750 °C (Schmidt, Taylor, 2014; Schmidt *et al*., 2015; Cornelissen *et al*., 2016) and cooled down slowly below the main pyrolysis zone when new feedstock layers were added to 150–450 °C depending on the duration of the batch before final quenching (Cornelissen *et al*., 2016).

Char particles of two plant materials were further ground in a grinding machine to make it fine powder with the char size similar to chars of sawdust and rice husk. Biochars were assessed for contents of nitrogen, phosphorus, potassium, total ash, electrical conductivity, pH and water holding capacity at the Chemical Laboratory of Nepal Academy of Science and Technology (NAST) in July 2017. Details of the biochar properties are presented in Table 2. The pH was determined by 1:2.5 biochar water suspension (Jackson, 1967). Organic matter content (Walkley, Black, 1934), Nitrogen (Micro-Kjeldahl, Bremner, Mulvaney, 1982), available phosphorus (Olsen *et al*., 1954) and available potassium (Ammonium acetate method; Jackson, 1967) were analyzed in the laboratories.

Water holding capacity of biochar was determined by Keen Raczkowski method (Piper, 1942). In this method, the Keen's box fitted with a filter paper was weighed on an electronic balance. The Keen's box was then packed with biochar sample by adding small quantity at a time. Excess biochar was removed with a spatula to bring the biochar inside the box to the level of the top of the box. The Keen's box with air dry biochar was weighed. The box with biochar placed in a Petri dish containing water to a depth of ¼ inch and it was left overnight. The next day the box was removed from the Petri dish and the excess water was allowed to drain out. Then the Keen's box was weighed. The water holding capacity was calculated from the gain in weight and the result was expressed in percentage (Baruah, Barthakur, 1999).

Experimental setup

The experiment was conducted to assess the effectiveness of biochars of different feedstock on the yield and yield attributes of potato; yield loss by the red ants and economic benefit. An experiment was conducted at Jiri in 2018 and Pawati in 2019 during the spring-summer season. An early variety 'Desiree' (Urgenta × Depesche) was used in the experiment. Potato tubers were planted in the first week of February and harvested in the fourth week of May in both the years. The experimental design was a randomized complete block with 6 replications and five treatments (Table 1). Plot size of 7.2 m^2 was maintained with the spacing of 60 cm for rows and 25 cm for plants, row length 3 m including 12 plants per row and 4 rows per plot. Thus, the whole plot was selected for yield and yield attributes. Fertilizers at the rate of 100:100:60 kg N : P_2O_5 : K_2O with 20 t ha^{-1} of FYM were applied on the rows and mixed with soil before planting. Biochars were applied at the rate of 2 t ha^{-1}. After planting, seed tubers were covered with an equal amount of biochar (Fig. 2). Without disturbing biochar, seed tubers were covered with the soil making ridges of 15 cm height. Seed sized tubers (25–50 g size) planted at a depth of 10 cm in the ridges.

Table 1. Treatment details for the experiment in 6 replications

Serial Number	Treatments
1	No Biochar
2	*Ipomoea carnea* var. *fistulosa*
3	*Lantana camara*
4	Rice husk
5	Saw dust

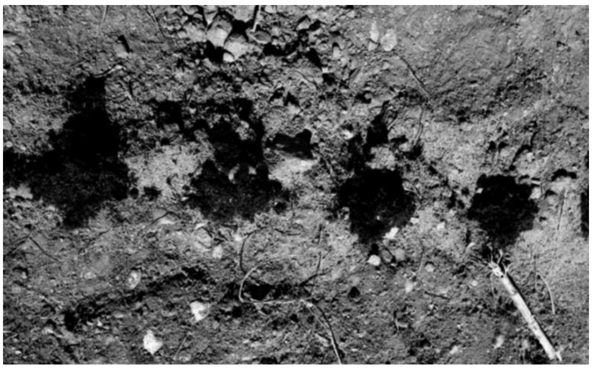
Figure 2. Method of biochar application in the field

Data observation

Observations were recorded on plant uniformity, ground cover, plant height, number of main stems per plant, percentage of number and weight of undersize, seed size and oversize tubers, number of tubers per plant, the weight of tubers per plant, total yield, and yield loss by the red ants and marketable yield. Plant and tuber attributes were recorded according to the field book of NPRP (NPRP, 2014). For example, plant uniformity (1–5 scale, 5 is 100% of plants uniform), ground cover (%), plant height, number of main stems per plant were recorded on 75 days of planting whereas rest of the parameters were recorded at harvesting.

For red ant infestation, number of damaged tubers, the weight of damaged tubers, percentage of damage, number of injuries per kg tubers, and tubers damage index (TDI) were recorded as the procedure applied by Sharma *et al*. (2017). Tubers Damage Index (TDI) value (0.00 to 1) was calculated based on the percentage of damaged tubers and the number of injuries per kilogram of tubers. Lower the TDI value, higher is the resistance against red ants. A formula developed by Sharma *et al*. (2015) was used to calculate the TDI value (Eq. 1).

Data analysis

Data were managed in a spreadsheet and analyzed with GenStat version 18 (VSN International, 2015) software for windows. Analysis of variance was used to determine statistically significant differences between means. Post hoc analysis was done by Duncan's Multiple Range Test. Standard errors of the means were determined for all significant data. At first, separate analysis for two locations was done and combined analysis was undertaken to determine conclusive results.

$$TDI\ value = \frac{Percentage\ of\ damaged\ tubers\ (a) + Number\ of\ injuries\ on\ per\ kg\ of\ tubers\ (b)}{The\ highest\ value\ of\ a\ sum\ of\ (a)\ and\ (b)\ of\ the\ same\ replication} \quad (1)$$

Results

Properties of biochar

Laboratory analysis of biochar showed that the biochar produced from *Lantana camara* L. contained higher water holding capacity, phosphorus and total nitrogen than the other biochars (Table 2). Total ash, potassium and electrical conductivity were higher in sawdust biochar compared to others. The pH value was the greatest in the biochar produced from *Ipomoea carnea* var. *fistulosa*. Nutrients and other properties may vary with the type of biochar (Kochanek, 2014). The nutrient content, ash content and other properties greatly differed when biochars were produced from Sugarcane Trash and Green Wastes (Upadhyay, 2015).

Table 2. Properties of biochar used in the experiment in 2018 and 2019

SN	Parameters	LC	IC	RH	SD
1	Water holding capacity, %	17.4	12.8	13.2	9.9
2	pH	9.6	9.9	8.03	9.2
3	Electrical conductivity, dS	3.8	3.1	3.3	8.5
4	Total ash, %	11.0	10.0	8.0	12.0
5	Potassium, ppm	10.4	5.3	8.0	12.7
6	Phosphorus, ppm	3.41	3.37	2.46	2.13
7	Total nitrogen, %	0.43	0.28	0.32	0.38

LC = *Lantana camara*, IC = *Ipomoea carnea*, RH = rice husk, SD = saw dust

Biochar effects on yield attributes of potato at Jiri in 2018

Among the plant characteristics (Table 3), significant differences (P = <0.05) were observed for ground cover, plant height and the number of main stems per plant. The differences were also observed for the percentage of the number of undersized tubers, percentage of the weight of oversize tubers and weight of tubers per plant (Table 4), total yield, yield loss by red ants and marketable yield (Fig. 3). Plant uniformity (Table 3), per cent of the weight of undersized tubers, number of seed size tubers, the weight of seed size tubers, number of oversize tubers and number of tubers per plant remained statistically non-significant (Table 4). The effect of no biochar was greater on ground cover followed by *Ipomoea carnea* whereas all biochars had similar but greater positive effect on plant height and the number of main stems per plant compared to the effect of no biochar. Undersize, seed size and oversize tubers were further measured to their number and weight (Table 4). The minimum percentage of the number of undersized tubers was recorded in the plots treated with *Lantana camara* biochar. The percentage of the weight of oversize tubers was higher in biochar-added plots compared no biochar-added plots except rice husk biochar applied plots. Weight of tubers per plant was greater in biochar treated plots compared to no biochar. Among the biochars, biochar produced from *Lantana camara* produced a significantly greater weight of tubers per plant compared to other biochars. Biochars were also effective for increasing total yield compared to no biochar. However, the influence of all biochars was similar for total yield. Yield loss by red ants was less in the plots treated with *Lantana camamra* and rice husk biochars. Marketable yield was higher in biochar-added plots showing *Lantana camara* biochar the most effective to produce marketable yield followed by rice husk and sawdust biochar.

Table 3. Effect of biochar on plant characteristics of potato at Jiri in 2018

Treatment	Uniformity (1–5)	Ground cover, %	Plant height, cm	No. of main stems plant^{-1}
NB	4.0	90±0.0 d	32.0±0.00 a	3.0±0.00 a
IC	3.7	84.2±0.03 c	27.7±0.16 b	4.5±0.63 b
LC	4.2	75.8±0.02 a	27.5±0.24 ab	3.8±0.21 ab
RH	3.7	82.5±0.01 bc	27.2±0.28 b	4.1±0.33 b
SD	3.8	79.2±0.0 2 ab	26.4±0.23 b	4.2±0.31 b
LSD (0.05)α0.05	0.71	3.9	3.09	0.79
CV (%)	15.2	4.0	9.1	16.9

NB = no biochar, LC = *Lantana camara*, IC = *Ipomoea carnea*, RH = rice husk, SD = sawdust. The means followed by the same letter on the same column are not significantly different at α 0.05 by Duncan's Multiple Range Test. The ± values represent standard error of the mean.

Table 4. Effect of biochar on tuber characteristics of potato at Jiri in 2018

Treatment	Tuber size distribution, %						No. of tubers plant^{-1}	Weight of tubers plant^{-1}
	Undersize (<20 g)		Seed size (20–50 g)		Oversize (>50 g)			
	No.	Weight	No.	Weight	No.	Weight		
NB	37.3 ± 1.26 b	15.1	49.1	59.2	13.6	25.7 ± 3.62 a	5.1	267.1 ± 14.72 a
IC	36.3 ± 0.91 b	11.1	44.6	51.4	19.0	37.6 ± 2.61 b	5.6	309.8 ± 17.14 b
LC	29.2 ± 2.19 a	10.3	54.6	56.9	16.2	32.8 ± 2.49 b	5.6	326.6 ± 24.64 c
RH	37.2 ± 1.78 b	13.8	49.2	54.4	13.6	31.8 ± 3.02 ab	5.4	276.7 ± 15.02 b
SD	35.7 ± 1.83 b	13.3	44.9	50.5	19.4	36.2 ± 2.80 b	5.7	302.5 ± 17.13 b
LSD (0.05)	5.22	3.95	8.22	8.68	6.24	6.18	3.3	17.35
CV (%)	12.3	25.8	14.1	13.2	31.7	15.6	9	10.1

NB = no biochar, LC = *Lantana camara*, IC = *Ipomoea carnea*, RH = rice husk, SD = sawdust. The columns of the same series followed by the same letter are not significantly different at α 0.05 by Duncan's Multiple Range Test. The ± values represent standard error of the mean.

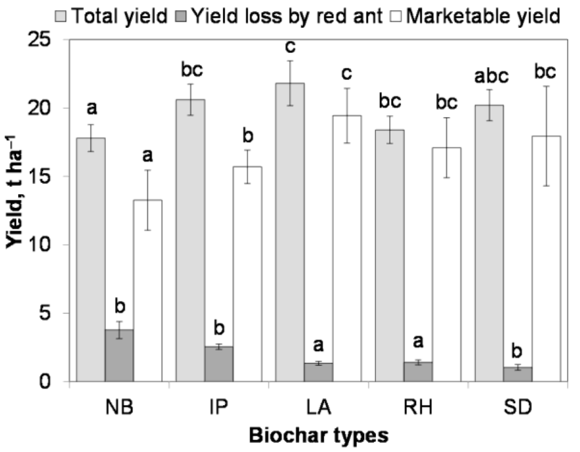

Figure 3. Effect of biochar on yields of potato at Jiri in 2018. NB = no biochar, LC = *Lantana camara*, IC = *Ipomoea carnea*, RH = rice husk, SD = sawdust. The columns of the same series followed by the same letter are not significantly different at α 0.05 by Duncan's Multiple Range Test. The bars represent standard error of the mean.

Biochar effects on red ant infestation on potato at Jiri in 2018

The number of tubers per plot was greater in the plots treated with biochars of *Ipomoea carnea*, *Lantana camara* and no biochar (Table 5). The percentage of damaged tubers was less in plots with biochar than the plots with no biochar; indicating a beneficial effect of biochar on red ant management. Biochars of *Lantana camara*, rice husk and sawdust produced less per cent of damaged tubers and weight of damaged tubers. The number of injuries per kg of tubers and Tubers damage index was less in the plots treated with *Lantana camara* and rice husk biochar. The TDI value showed that the tubers were less damaged in *Lantana camara* (TDI value = <0.5), medium damaged in rice husk (TDI value = 0.5–0.75) and highly damaged (TDI value = >0.75) in remaining treatments, according to the categories developed by Sharma *et al*. (2015). The variety 'Desiree' was characterized as highly susceptible to red ants with 49.7 to 77% of damaged tubers (Joshi, 1998).

Table 5. Effect of biochar on red ant infestation on potato at Jiri in 2018

Treatment	No. of tubers plot^{-1}	% of damaged tubers	Weight of damaged tubers, kg	No. of injuries kg^{-1}	Tubers damage index
NB	313.5 ± 16.65 b	23.3 ± 1.43 c	2.72 ± 0.450 c	43.2 ± 3.94 bc	0.97 ± 0.023 b
IC	326.7 ± 18.97 b	9.6 ± 0.84 b	1.83 ± 0.143 b	47.6 ± 4.00 c	0.85 ± 0.056 b
LC	303.8 ± 14.37 b	4.7 ± 0.81 a	0.97 ± 0.099 a	26.4 ± 4.86 a	0.48 ± 0.096 a
RH	252.7 ± 18.01 a	5.3 ± 1.15 a	1.02 ± 0.130 a	30.3 ± 3.18 ab	0.55 ± 0.081 a
SD	240.5 ± 9.50 a	7.4 ± 1.85 ab	0.75 ± 0.152 a	45.8 ± 6.89 c	0.78 ± 0.070 b
LSD (0.05)	47.99	3.373	0.707	31.66	0.194
CV (%)	13.9	27.8	31.6	29.4	22.2

NB = no biochar, LC = *Lantana camara*, IC = *Ipomoea carnea*, RH = rice husk, SD = sawdust. The means followed by the same letter on the same column are not significantly different at α 0.05 by Duncan's Multiple Range Test. The ± values represent standard error of the mean.

Biochar effects on yield attributes of potato at Pawati in 2019

In Pawati, significant differences (P = <0.05) were observed for ground cover, plant height and the number of main stems per plant (Table 6). The differences were also observed for the percentage of the number of undersized tubers, percentage of the weight of undersized tubers, number of tubers per plant, the weight of tubers per plant (Table 7), total yield, yield loss by red ants and marketable yield (Fig. 4). Plant uniformity (Table 6), percentage of the number of seed size tubers, the weight of seed size tubers, number of oversize tubers and weight of oversize tubers remained non-significant. The effect of no biochar was greater on ground cover and plant height whereas all biochars had similar but greater positive effect on the number of main stems per plant compared to the effect of no biochar. The minimum percentage of the number of undersized tubers and the percentage of the weight of undersized tubers was recorded in the plots treated with *Lantana camara* biochar. *Lantana camara* biochar also produced the highest number of tubers per plant and weight of tubers per plant. The effects of *Lantana camara*, sawdust and rice husk biochars were greater on total yield. Yield lossless in biochar-added plots compared to no biochar. Among the biochars, *Lantana camara* showed less yield loss by red ants followed by rice husk and sawdust biochar. Biochars were also beneficial for producing marketable yield showing *Lantana camara* biochar the most effective to produce marketable yield followed by sawdust and rice husk biochar.

Table 6. Effect of biochar on plant characteristics of potato at Pawati in 2019

Treatment	Uniformity (1–5)	Ground cover, %	Plant height, cm	No. of main stems plant^{-1}
NB	4.3	90.5 ± 0.0 d	32.0 ± 0.00 b	3.0 ± 0.00 a
IC	3.7	84.7 ± 0.03 c	27.7 ± 0.16 a	3.7 ± 0.63 b
LC	4.2	77.3 ± 0.02 a	27.5 ± 0.24 a	3.7 ± 0.21 b
RH	3.7	83.3 ± 0.01 bc	27.2 ± 0.28 a	3.8 ± 0.33 b
SD	3.8	79.5 ± 0.02 ab	26.4 ± 0.23 a	4.2 ± 0.31 b
LSD (0.05)	0.71	4.40	3.09	0.616
CV (%)	15.0	4.4	9.1	13.7

NB = no biochar, LC = *Lantana camara*, IC = *Ipomoea carnea*, RH = rice husk, SD = saw dust. The means followed by same letter on the same column are not significantly different at α 0.05 by Duncan's Multiple Range Test. The ± values represent standard error of the mean.

Table 7. Effect of biochar on tuber characteristics of potato at Pawati in 2019

Biochar	Tuber size distribution, %						No. of tubers plant^{-1}	Weight of tubers plant^{-1}
	Under size (<20 g)		Seed size (20–50 g)		Oversize (>50 g)			
	No.	Weight	No.	Weight	No.	Weight		
NB	34.3 ± 1.26 b	14.6 ± 0.79 b	48.9	47.9	16.8	37.5	5.3 ± 0.27 a	240.4 ± 14.72 a
IC	35.6 ± 0.91 b	13.3 ± 0.38 b	44.8	45.2	19.6	41.5	5.6 ± 0.34 ab	252.1 ± 17.14 a
LC	29.7 ± 2.19 a	9.8 ± 0.43 a	48.0	48.3	22.3	42.0	6.1 ± 0.26 b	286.1 ± 24.64 b
RH	35.5 ± 1.78 b	13.8 ± 1.07 b	44.7	45.3	19.7	40.9	5.7 ± 0.21 ab	259.1 ± 15.02 ab
SD	32.3 ± 1.83 ab	12.8 ± 0.85 b	47.9	45.0	19.7	42.2	6.0 ± 0.29 b	263.6 ± 17.13 ab
LSD (0.05)	3.98	1.81	4.62	5.11	4.55	5.66	0.52	27.99
CV (%)	9.9	11.7	8.2	9.2	19.3	11.5	7.3	8.9

NB = no biochar, LC = *Lantana camara*, IC = *Ipomoea carnea*, RH = rice husk, SD = sawdust. The means followed by the same letter on the same column are not significantly different at α 0.05 by Duncan's Multiple Range Test. The ± values represent standard error of the mean.

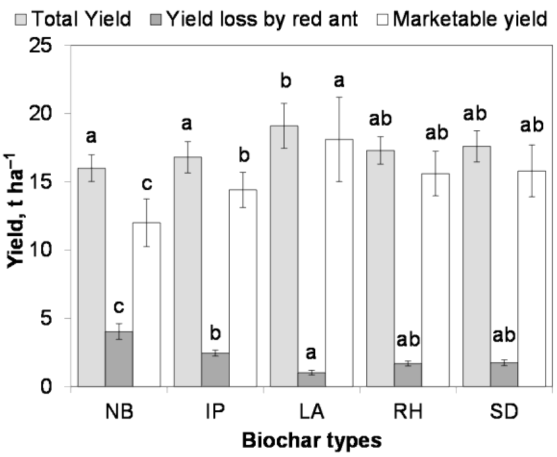

Figure 4. Effect of biochar on yields of potato at Pawati in 2019. The columns of the same series followed by the same letter are not significantly different at α 0.05 by Duncan's Multiple Range Test. The bars represent standard error of the mean

Biochar effects on red ant infestation on potato at Pawati in 2019

The results revealed that the greatest number of tubers per plot was produced by *Ipomoea carnea* followed by *Lantana camara* and no biochar (Table 8). The per cent of damaged tubers was less in biochar-added plots than no biochar plots. Biochar produced from *Lantana camara* had a significantly greater positive effect on the percentage of damaged tubers, weight of damaged tubers. The number of injuries per kg of tubers was less in the plots treated with sawdust followed by *Lantana camara* biochar. The TDI value was the least for sawdust followed by *Lantana camara* whereas it was significantly larger for no biochar. According to the category, the TDI value showed that the less damage (TDI value = <0.5) tubers were observed in sawdust and *Lantana camara*, medium damaged in rice husk (TDI value = 0.5–0.75) and high damage (TDI value = >0.75) in remaining treatments.

Table 8. Effect of biochar on red ant infestation on potato at Pawati in 2019

Biochar	No. of tubers plot^{-1}	% of damaged tubers	Weight of damaged tubers	No. of injuries kg^{-1}	Tubers damage index
NB	280.3 ± 13.07 b	25.2 ± 1.07 d	2.90 ± 0.421 c	49.2 ± 3.43 c	0.96 ± 0.038 d
IC	292 ± 11.72 b	12.6 ± 0.83 c	1.77 ± 158 b	46.5 ± 3.90 c	0.77 ± 0.055 c
LC	282 ± 13.41 b	4.6 ± 0.39 a	0.73 ± 0.126 a	28.3 ± 4.55 a	0.42 ± 0.051 a
RH	233 ± 10.48 a	9.2 ± 1.05 b	1.22 ± 0.128 ab	35.3 ± 4.93 b	0.57 ± 0.045 b
SD	230.2 ± 7.04 a	7.8 ± 1.28 b	1.25 ± 0.150 ab	21.8 ± 2.43 c	0.38 ± 0.041 a
LSD (0.05)	34.3	2.939	0.647	10.92	0.142
CV (%)	10.8	20.5	30.3	25	18.9

NB = no biochar, LC = *Lantana camara*, IC = *Ipomoea carnea*, RH = rice husk, SD = sawdust. The means followed by the same letter on the same column are not significantly different at α 0.05 by Duncan's Multiple Range Test. The ± values represent standard error of the mean.

Discussion

Biochar effects were encouraging on yield attributes of potato. Yields were higher in 2018 than in 2019. It should be linked with the consistent trend of temperatures and higher rainfall during March-April in 2018 (Fig. 1), when the tuber initiation and development stage was started. The dry nature of the soil in Jiri received more moisture during the tuber formation period in 2018. The biochar produced from *Lantana camara* was more effective, possibly due to favourable water holding capacity, ash content and NPK content (Table 2).

Effect of biochar may rely on growth conditions and composition of soil medium. For instance, biochar application may not bring significant soil quality and crop productivity improvements to high-input agricultural systems (Boersma *et al*., 2017). The number of stems per hill, the number of tubers per hill, weight of tubers per hill and yield were increased with the application of biochar plus recommended fertilizer dose (Ali, 2017). Our study results were also in line with these results. Similarly, adding biochar to potato plants grown in sandy soil improved plant growth, plant chemical compositions, tuber yield and its components, with good tuber quality (Youssef *et al*., 2017). Adding biochar to the soil with the fully irrigated condition without phosphorus fertilizer and arbuscular mycorrhiza increased the biomass of potato (Liu *et al*., 2016).

On the other hand, a single rotation of wood biochar to soil did not affect growth or harvest yield of potato (Jay *et al*., 2015). There was no consistent effect of green waste biochar on growth of true potato seedlings and node cuttings of true potato seedlings when biochar was applied to sand medium nourished with additional nutrient solution (Upadhyay *et al*., 2014). Nair *et al*. (2014) also found no significant effect of biochar on growth and marketable number and weight of potato. Application of plantain peel biochar to potato under freshwater and wastewater did not increase yield (Nzediegwu *et al*., 2019) whereas it varied between biochars in the present study. For example, the effect of biochar produced from *Ipomoea carnea*, rice husk and sawdust was similar to the influence of no biochar; and biochar of *Lantana camara* was effective for increasing the yields.

In a recent study carried out by Robb and Joseph (2019), biochar mixed with NPK increased the total yield per hectare of potatoes from 38.8 tonnes to 58.1 tonnes, a 53 % increase in which the 20% biochar substitution delivered both the highest yield and highest tuber productivity per plant. According to Liu *et al*. (2013), biochar applications increased potato yields approximately 19%, based upon a meta-analysis of 59 pot experiments from 21 countries and 57 field experiments from 21 countries. When situation favours to 19% yield increase in present yield (14.7 t ha^{-1}) of potato in Nepal, it will reach 17.5 t ha^{-1} which could be a significant contribution to substitute import of potato from neighbouring countries. In the fiscal year 2018/19, about 347 309 metric tonnes of potatoes were imported to Nepal (TEPC, 2019). Thus, the increased production will be 539 049 metric tonnes when 19% yield increase will occur by biochar application. If not the same but 50% of the 19% yield increase could be added, a considerable amount of import would be reduced.

Likewise, Farooque *et al*. (2020) showed that the maximum potato yields (30.5 t ha^{-1}) could be achieved by the combined application of biochar and recommended dose of synthetic fertilizers in comparison with the control treatment. Our study showed a significant increase in potato yield by biochar in combination with recommended dose of fertilizers. A recent study showed that if potato crop irrigated fully with phosphorus addition to soil and not inoculated with AM fungi, then the addition of biochar can increase potato yield (Spudsmart, 2020). In the present study, results indicate the positive effect of biochar on yield increase.

Biochar could be a useful additive in the production and formulation of biopesticides (Sayed *et al*., 2018). Some findings have been reported on the influence of biochar on the occurrence of insect pests. For instance, biochar amendment to rice fields had negative impacts on the rice brown planthoppers when applied at the level of 200 g kg^{-1} of soil (Hou *et al*., 2015). Elad *et al*. (2015) indicated that biochar induced systemic resistance to the broad mite pest (*Polyphagotarsonemus latus* Banks) on pepper. The abundance of soil insects was reduced due to the increased rate of rice husk biochar in potato fields (Meilin, Rubiana, 2018). Some preliminary observations on charcoal effects on small red ants showed that brinjal seeds in the 6 pots with 30% charcoal plus soil were untouched by small red ants while the seeds in control pots were eaten (Reddy, 2007). The ant distribution could be connected to the properties of biochar amended soil (Castracari *et al*., 2015). However, these ants were different from red ants of potato and their damaging behaviour was different. Yet, the literature on the efficacy of biochar to control potato red ants are very limited. Our findings would be an avenue for further confirmation of the influence of biochar on red ant infestation on the potato.

The impact of biochar needed to be observed in succeeding years since the impact of biochar is long-term. We did not examine the effects of biochar application in soil fertility; however, it was important for developing a long-term soil management plan. We also did not evaluate soil and plant nutrients before planting and after harvest so that the information on soil nutrient status could not be explained. We observed it in two locations where farmers were facing the problem of red ants. The results emphasized that the application of biochar was beneficial for saving yields where the considerable loss of potatoes is occurred due to red ant infestation. The reason behind the low infestation of red ants with the biochar application is a matter of study. In our case, there was a possibility that some compounds might be left in the biochar from the pyrolysis process (Kon-Tiki 680–750 °C) which acted as a repellent. Besides, there could be an indirect impact of biochar that it improved the immunity of the plants through increased water availability, hence making them more resistant to pests and other threats. Yet, is there any specific chemical inherent to the biochar may toxic or repel the red ants? Or its powdery mass may suffocate to the ants or absorb water from their body? Nepalese traditional farmers apply wood ash to control ants and aphids in the kitchen garden; they believe ash powder suffocates and absorbs water from their body. Can we expect similar effects of fine biochar on red ants? These are the questions that should be answered from future experiments.

Conclusions

Biochar application with the rate of 2 t ha^{-1} an in combination with recommended farmyard manure and NPK fertilizers increased total yield and marketable yield. Among the biochars, *Lantana camara*, sawdust and rice husk showed less yield loss by red ants compared to no biochar. Tubers damage index was less in the plots with the biochar of *Lantana camara* followed by rice husk and sawdust. The yields saved from red ants with the application of biochar, specifically the biochar from *Lantana camara*, were significantly higher than no biochar. Thus, biochar application to potato fields in red ant prone areas could increase marketable yield.

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Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author contributions

KPU – study conception and design, analysis and interpretation of data, drafting of the manuscript and approval of the final manuscript;
NBD – carried out the experiment on outreach site of Kabre, Dolakha;
PNS – acquisition of data of insects;
JDN – acquisition of data of experiment;
JS – critical revision and approval of the final manuscript.

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