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NUTRIENT RETURN THROUGH LITTERFALL FROM POPLAR PLANTATION HAVING DIFFERENT SPACINGS IN AN AGROFORESTRY SYSTEM

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ABSTRACT

An investigation into nutrient return via litterfall was conducted in a poplar (*Populus deltoides* Bartr.) plantation employing three distinct spacing configurations [5 x 3 m, 7 x 3 m (paired at 2.5 m), and 8 x 2.5 m] within an agroforestry system over the plantation's 4th, 5th, and 6th years of growth. After six years, trees planted at 8 x 2.5 m spacing exhibited significantly greater diameters at breast height (22.05 cm) and heights (19.47 m) compared to those at the other spacings. Litterfall accumulation over the 4th, 5th, and 6th years was statistically highest in the 7 x 3 m (paired row) spacing, with totals of 6.54, 7.61, and 7.53 t/ha, respectively, and lowest in the 8 x 2.5 m spacing, with totals of 4.55, 4.90, and 5.40 t/ha, respectively. The average nutrient return of nitrogen (N), phosphorus (P), and potassium (K) over these years was significantly greater in the 7 x 3 m (paired row) spacing, with values of 65.41, 7.38, and 55.53 kg/ha, respectively, compared to the other spacings. Soil organic carbon (OC), available N, P, and K content were all elevated compared to initial levels, with the highest concentrations found under the 7 x 3 m (paired row) spacing, measuring 4.47 g/kg, 158.3 kg/ha, 18.23 kg/ha, and 199.1 kg/ha, respectively. These findings suggest that poplar-based agroforestry systems contribute positively to soil health through the addition of litterfall. Nonetheless, further research is needed to quantify the contribution of litterfall nutrients to the overall nutrient requirements of the agroforestry system.

Keywords: Available nutrients, growth parameters, nutrient cycling, *Populus deltoides*

Poplar (*Populus deltoides* Bartr.) cultivation across various land use systems significantly addresses economic, social, and environmental concerns. Its broad acceptance is attributed to its easy regeneration, readily available quality planting material, minimal competition with agricultural crops, tolerance to pruning, short harvest cycle (5–6 years), reliable market demand, and lucrative returns (Kaur *et al.*, 2021). In north-western India, farmers have increasingly adopted poplar cultivation (Chavan and Dhillon, 2019), making it a highly effective on-farm asset that offers low-risk investment opportunities with the potential for returns surpassing other agricultural options. Poplar's deciduous nature results in complete leaf drop during winter, and its plantations positively impact soil physico-chemical properties by accumulating significant amounts of nutrients through litterfall compared to other deciduous species (Singh *et al.*, 2007). This nutrient cycling is crucial for regulating organic matter buildup, nutrient input and output, nutrient replenishment, biodiversity conservation, and other ecological processes (Giweta, 2020). The nutrient return to the soil from leaf litter is influenced by factors such as tree age, spacing, litter quality, weather conditions, and the dynamics of nutrient concentrations during decomposition (Rana *et al.*, 2007; Singh *et al.*, 2007). These added nutrients play a vital role in maintaining soil fertility and promoting sustainable land management practices.

Information on nutrient addition through litterfall in poplar-based agroforestry systems with varying spacings remains limited. This knowledge is essential for evaluating the sustainability of such systems. Consequently, this study was undertaken to assess litterfall and nutrient return across three different spacings in a poplar-based agroforestry system during the 4th to 6th years of tree growth. Additionally, the study aimed to analyze changes in soil organic carbon and nutrient status following six years of poplar cultivation.

MATERIALS AND METHODS

Climate and study site

The study was conducted in a poplar-based agroforestry system located in the Ludhiana district of Punjab, India situated at 30° 05' N latitude and 75° 40' E longitude, with an elevation of 247 meters above mean sea level. The climate in this region is subtropical, characterized by a prolonged dry season from late September to early June and a wet season from late June to early September. On average, this part of the country receives approximately 750 mm of rainfall annually, which is unevenly distributed, with the majority falling between July and September during the monsoon season. The study was carried out in

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a poplar-based agroforestry system in its 4th year, established at three different spacings: 5 x 3 meters, 7 x 3 meters (paired at 2.5 meters), and 8 x 2.5 meters, at the Forestry Research Farm of Punjab Agricultural University, Ludhiana, India. The tree densities for each spacing were as follows: 665 trees/ha for 5 x 3 meters, 710 trees/ha for 7 x 3 meters (paired at 2.5 meters), and 500 trees/ha for 8 x 2.5 meters. The surface soil at the study site was sandy loam, with a pH of 8.1, electrical conductivity (EC) of 0.27 dS/m, organic carbon content of 3.22 g/kg, and available nutrients as follows: nitrogen (N) 136.2 kg/ha, phosphorus (P) 13.72 kg/ha, and potassium (K) 188.4 kg/ha in the 0-15 cm surface layer at the time of plant establishment (February 2012). Wheat was intercropped in the plantation annually during the winter season, specifically in the second week of November, following recommended cultural practices. The recommended fertilizer application for wheat was 110 kg N, 60 kg P_2O_5, and 30 kg K_2O per hectare. Of these, half of the nitrogen (N) and the full doses of phosphorus (P) and potassium (K) were applied at sowing, with the remaining nitrogen applied during the first irrigation. Growth parameters were recorded in February. Tree height was measured from the base of the tree to the growing tip using Ravi's multimeter at the end of the 4th, 5th, and 6th years of growth. Girth at breast height (GBH) was measured with a tape, and diameter at breast height (DBH) was calculated by dividing GBH by 3.14.

Litterfall collection and analysis

Litterfall was collected in the agroforestry system from the onset of leaf drop in October until the trees were fully leafless in January during the 4th, 5th, and 6th years of plant growth. Each spacing was replicated four times. In each replication, four wooden litter traps, measuring 1 m x 1 m x 10 cm, were randomly placed. Each trap was supported by pegs fixed at its four corners, which were set to a height of 30 cm. Among the four traps, one was positioned at the midpoint of the alley between two tree rows, one was placed directly within a tree row, and the remaining two were located at the quarter points between the two tree rows (Sreemannarayana, 2004; Singh *et al.*, 2023). Litterfall was collected from these traps in paper bags at fortnightly intervals during the leaf-shedding period. The litter collected from each interval was combined to determine the total litterfall for each month. The fresh weight of the collected litter was recorded, and a representative 50 g sample was taken from each replication for further analysis. These samples were oven-dried at 65°C until reaching a constant weight to calculate the dry weight of the litterfall. Subsequently, the dried samples were ground using an electric grinder equipped with stainless steel blades.

To determine the total nitrogen (N) in the litterfall, a known weight of the sample was digested using concentrated sulfuric acid (H_2SO_4). For the analysis of other nutrients, the sample was digested with a diacid mixture of nitric acid (HNO_3) and perchloric acid ($HClO_4$) in a 3:1 ratio. Nitrogen content in the digest was quantified through distillation using a Kjeldahl assembly, with boric acid as the indicator solution (Jackson, 1973). Phosphorus (P) was measured using the vanadomolybdate yellow colorimetric method within the nitric acid system (Jackson, 1973). Potassium (K) was determined using a flame photometer. Nutrient concentrations were assessed separately for each month, and the total nutrient return through litterfall was calculated based on both the nutrient concentration and the total quantity of litterfall for each respective month.

Soil samples from the surface depth (0–15 cm) were collected in April, after the wheat harvest, from the site where poplar trees had been growing for six years. To create a composite soil sample for each replication, soil was collected from six locations within the alley between two tree rows: two samples from the midpoint of the alley and two samples from each of the quarter points along the tree rows. These samples were analyzed for soil organic carbon (SOC) and available nitrogen (N), phosphorus (P), and potassium (K) using standard methods (Jackson, 1973). The data were statistically analyzed using a randomized block design, with spacing and months considered as treatments (Panse and Sukhatme, 1985).

RESULTS AND DISCUSSION

Growth parameters of poplar

The growth performance of trees is influenced by factors such as the genetic constitution of the species, site quality, and management practices. In this study, poplar trees exhibited a general upward growth trend with age. Tree spacing significantly impacted both diameter at breast height (DBH) and height, with the widest spacing showing the greatest values after 4, 5, and 6 years of growth (Fig. 1). Specifically, from the fourth to the sixth year, DBH and height increased from 19.71 to 22.05 cm and from 17.50 to 19.47 m, respectively, in the 8 x 2.5 m spacing. After six years, the 8 x 2.5 m spacing showed a 15.8% increase in DBH and a 9.9% increase in height compared to the 7 x 3 m (paired row) spacing. The superior growth in the wider spacing is likely due to the increased availability of space, which may enhance light penetration and promote the survival of lower branches. This allows for extended photosynthetic activity and sustained growth over a longer period. These observations align with findings from other studies, which also reported

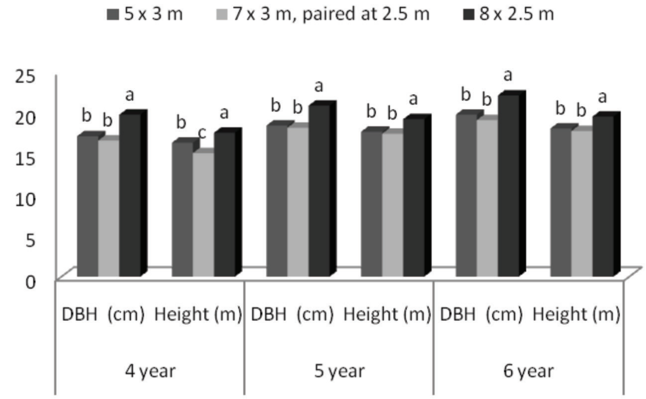

Fig. 1. Growth parameters of poplar plantation during 4th to 6th year of age under different spacings. Bars with different letters vary significantly at *p≤0.05* for DBH or height during its 4th, 5th and 6th year of age separately under different spacings A

improved growth in wider spacing configurations (Kumara *et al.*, 2021; Kaur *et al.*, 2021). Diameter growth is closely related to photosynthetic biomass and efficiency, as well as crown ratio (Zhang *et al.*, 2014). Trees planted at wider spacings are able to capture more sunlight and develop a more expansive canopy compared to those planted at closer spacings (Kumara *et al.*, 2021).

Litterfall and its nutrient concentration

Litterfall addition across the four months and three spacing configurations varied significantly during the 4th, 5th, and 6th years of poplar growth (Table 1). Leaf shedding commenced in October and continued through January, with leaves decomposing upon contact with the soil due to microbial activity. The uniform dispersion of leaves by wind across plots minimizes significant differences in their distribution. As leaves remain on the germinated wheat plots, their decomposition, facilitated by applied irrigation and microbial activity, enhances the soil's organic carbon content (Lal *et al.*, 2000). The application of a second dose of nitrogen in December also aids in litterfall decomposition (Kaur and Singh, 2020). Among the months, litterfall was notably higher in December compared to other months, likely due to the senescence of a large number of leaves. In the 5th year, litterfall peaked at 3.76 t/ha in December, whereas the lowest was recorded in January of the 4th year at 0.65 t/ha. During the 6th year, the monthly litterfall followed the order: December (3.66 t/ha) > November (0.96 t/ha) > January (0.90 t/ha) > October (0.78 t/ha). These observations are consistent with previous studies, which reported increased litterfall with tree age (Vivanco and Austin, 2008; Singh, 2009) and highlighted the significant influence of winter months on leaf fall patterns (Rana *et al.*, 2007). On the other hand, Mishra *et al.* (2004) found that while tree age did not independently affect litterfall production, factors such as age, density, and basal area were critical to litter production. In our study, tree spacing significantly impacted litterfall. The highest litterfall addition (1.90 t/ha) was recorded in the 5th year for the 7 x 3 m (paired row) spacing, followed by 1.55 t/ha in the 5 x 3 m spacing, and the lowest was 1.23 t/ha in the 8 x 2.5 m spacing. The increased litter production in paired row spacing is attributed to the higher number of trees in that configuration. These results align with findings by Singh *et al.* (2007).

The highest concentrations of nitrogen (N), phosphorus (P), and potassium (K) were observed in

Table 1. Litterfall and nutrient concentration in poplar plantation during its 4th to 6th year in different months under variable spacings

Treatments	Litterfall (t/ha)			Nitrogen (%)			Phosphorus (%)			Potassium (%)		
	4	5	6	4	5	6	4	5	6	4	5	6
Months												
October	0.65	0.78	0.78	1.04	0.99	0.95	0.154	0.137	0.123	0.89	0.85	0.83
November	0.81	0.93	0.96	0.96	0.94	0.92	0.127	0.116	0.111	0.85	0.82	0.78
December	3.32	3.76	3.66	0.93	0.88	0.88	0.104	0.097	0.091	0.80	0.76	0.73
January	0.67	0.77	0.90	0.86	0.84	0.84	0.088	0.089	0.088	0.76	0.72	0.71
LSD (*p≤0.05*)	0.16	0.19	0.27	0.04	0.04	0.05	0.009	0.015	0.016	0.03	0.02	0.04
Spacings												
5 x 3 m	1.32	1.55	1.49	0.96	0.93	0.91	0.116	0.110	0.105	0.82	0.79	0.77
7 x 3 m, paired at 2.5 m	1.64	1.90	1.88	0.94	0.91	0.90	0.119	0.110	0.103	0.82	0.78	0.75
8 x 2.5 m	1.14	1.23	1.35	0.94	0.90	0.88	0.120	0.108	0.103	0.83	0.79	0.77
LSD (*p≤0.05*)	0.14	0.17	0.24	NS	NS	NS	NS	NS	NS	NS	NS	NS

October at the age of four years, with values of 1.04%, 0.154%, and 0.89%, respectively. On the other hand, the lowest concentrations were recorded in January at the age of six years, with values of 0.84%, 0.088%, and 0.71%, respectively. Nutrient concentrations varied significantly across months, showing a general decline over time, probably due to increased nutrient senescence as the months progressed from October to January. Despite differences in nutrient concentrations between months, variations in nutrient levels across different spacings were not significant, as the trees were planted on similar sites and were of the same age (Singh, 2009). Spacing did not substantially influence nutrient concentrations. Nonetheless, data indicates a trend of decreasing nutrient concentration with age and time. Among different spacings, the highest nitrogen concentration (0.96%) was observed at the age of four years in the 5 x 3 m spacing, while phosphorus (0.12%) and potassium (0.83%) concentrations were highest in the 8 x 2.5 m spacing. The observed decrease in nutrient concentration with age and time can be attributed to the dilution effect. This effect suggests that as plant biomass increases, the concentration of individual nutrients tends to decrease (Mohsin *et al.*, 1996; Singh *et al.*, 2020; Bisht *et al.*, 2020).

Nutrient return through litterfall

Nutrient return through litterfall for different macronutrients exhibited significant variation over the four months and three spacings (Table 2). During the 4th, 5th, and 6th years of cultivation, December consistently yielded the highest nutrient returns, while January recorded the lowest. Specifically, in December of the 5th year, the returns of nitrogen (N), phosphorus (P), and potassium (K) were 33.23 kg/ha, 3.66 kg/ha, and 28.45 kg/ha, respectively, which were significantly higher than those in other months. Among the different spacings, the 7 x 3 m (paired row) spacing produced the highest amounts of nutrients returned through litterfall, with 16.94 kg/ha of N, 1.96 kg/ha of P, and 14.57 kg/ha of K at the age of 5 years. This was followed by the 5 x 3 m spacing, which returned 14.29 kg/ha of N, 1.69 kg/ha of P, and 12.18 kg/ha of K, while the 8 x 2.5 m spacing recorded the lowest returns for these nutrients. The greater nutrient return in the paired row spacing is attributed to the higher number of trees in this configuration. Enhanced breakdown of leaf litter in this spacing likely contributes to improved soil nutritional quality. These findings are consistent with similar observations reported by Singh *et al.* (2007) and Nanda *et al.* (2021) in other tree species.

Total litterfall and nutrient return from a poplar-based agroforestry system with three different spacings across various growth years are presented in table 3. The average litterfall was highest in the 7 x 3 m (paired row) spacing, recording 7.23 t/ha, and lowest in the 8 x 2.5 m spacing, which yielded 4.95 t/ha. Interaction effects revealed that the highest litterfall occurred in the sixth year of the agroforestry system for the 7 x 3 m spacing (7.61 t/ha), while the lowest was observed in the fourth year for the 8 x 2.5 m spacing (4.55 t/ha). The return of nutrients through litterfall also varied significantly among the three spacings. The 7 x 3 m (paired row) spacing exhibited the highest nutrient return, followed by the 5 x 3 m spacing, with the 8 x 2.5 m spacing showing the lowest returns. The increased number of trees and denser canopies in the paired row spacing contributed to higher nutrient returns. Specifically, the returns of nitrogen (N), phosphorus (P), and potassium (K) ranged from 42.27 to 46.74 kg/ha, 5.05 to 5.07 kg/ha, and 37.13 to 40.64 kg/ha, respectively, in the 8

Table 2. Nutrient return in poplar plantation during its 4th to 6th year in different months under variable spacings

Treatments	Nitrogen (kg/ha)			Phosphorus (kg/ha)			Potassium (kg/ha)		
	4	5	6	4	5	6	4	5	6
Months									
October	6.80	7.69	7.43	1.00	1.05	0.96	5.80	6.57	6.43
November	7.79	8.69	8.79	1.03	1.08	1.06	6.91	7.58	7.46
December	30.86	33.23	32.17	3.40	3.66	3.32	26.40	28.45	26.83
January	5.77	6.49	7.63	0.59	0.69	0.78	5.11	5.60	6.37
LSD ($p \leq 0.05$)	1.11	1.32	1.50	0.15	0.13	0.16	0.86	0.88	0.90
Spacings									
5 x 3 m	12.62	14.29	13.43	1.49	1.69	1.52	10.72	12.18	11.25
7 x 3 m, paired at 2.5 m	15.22	16.94	16.89	1.76	1.96	1.82	13.16	14.57	13.91
8 x 2.5 m	10.57	10.84	11.68	1.27	1.22	1.26	9.28	9.40	10.16
LSD ($p \leq 0.05$)	0.96	1.14	1.29	0.13	0.12	0.14	0.75	0.76	0.78

Table 3. Total litterfall and nutrient return from poplar plantation having different spacings

Spacings	Poplar age (years)			Mean
	4	5	6	
Litterfall (t/ha)				
5 x 3 m	5.28	6.20	5.98	5.82
7 x 3 m, paired at 2.5 m	6.54	7.61	7.53	7.23
8 x 2.5 m	4.55	4.90	5.40	4.95
Mean	5.46	6.24	6.30	
LSD (*p≤0.05*): Age - 0.43, Spacing - 0.38, Age x Spacing - NS				
N return (kg/ha)				
5 x 3 m	50.50	57.18	53.74	53.80
7 x 3 m, paired at 2.5 m	60.88	67.79	67.56	65.41
8 x 2.5 m	42.27	43.38	46.74	44.13
Mean	51.22	56.11	56.01	
LSD (*p≤0.05*): Age – 2.66, Spacing – 3.46, Age x Spacing – NS				
P return (kg/ha)				
5 x 3 m	5.98	6.75	6.07	6.27
7 x 3 m, paired at 2.5 m	7.02	7.84	7.26	7.38
8 x 2.5 m	5.07	4.87	5.05	5.00
Mean	6.03	6.49	6.13	
LSD (*p≤0.05*): Age – 0.22, Spacing – 0.27, Age x Spacing – 0.47				
K return (kg/ha)				
5 x 3 m	42.90	48.72	45.01	45.54
7 x 3 m, paired at 2.5 m	52.65	58.30	55.64	55.53
8 x 2.5 m	37.13	37.61	40.64	38.46
Mean	44.23	48.21	47.10	
LSD (*p≤0.05*): Age – 2.51, Spacing – 2.64, Age x Spacing – NS				

x 2.5 m spacing across different years. On the other hand, the average nutrient returns in the 7 x 3 m (paired row) spacing were significantly higher, with 65.41 kg/ha of N, 7.38 kg/ha of P, and 55.53 kg/ha of K. This variability in nutrient returns is attributed to differences in nutrient concentration in the litterfall and the total amount of litterfall. These findings indicate that litterfall dynamics significantly influence nutrient return levels. Singh *et al.* (2007) observed that in a poplar-based agroforestry system, the overall return of nitrogen was higher while phosphorus was lower compared to other nutrients. Similarly, Nanda *et al.* (2021) and Singh *et al.* (2023) highlighted that litterfall addition contributed to increased nutrient content in Melia-based agroforestry systems, leading to a notable rise in macronutrient content.

Soil OC and nutrient status in poplar plantation

Soil organic carbon (SOC) levels were significantly influenced by tree spacing and increased from initial levels across different spacings (Table 4). SOC demonstrated a positive correlation with decreasing tree spacing, reaching its peak of 4.47 g/kg under the 5 x 3 m spacing. The SOC levels followed the order: 7 x 3 m (paired row) = 4.47 g/kg > 5 x 3 m = 4.23 g/kg > 8 x 2.5 m = 4.05 g/kg. The higher organic matter content in the soil can be attributed to the addition and decomposition of litterfall, which contributes to the soil's carbon pool. Factors contributing to SOC enrichment in poplar agroforestry systems include litter addition, annual recycling of fine root biomass, root exudates, and reduced organic matter oxidation under tree canopy cover (Sharma *et al.*, 2015; Bisht *et al.*, 2020). The increased SOC in the 7 x 3 m (paired row) spacing, despite being equal to the 5 x 3 m spacing, could be related to the higher amount of litterfall resulting from the greater number of trees per hectare in this configuration.

The available nitrogen (N) was significantly higher in the 7 x 3 m (paired row) spacing (158.3 kg/ha) and the 5 x 3 m spacing (155.4 kg/ha) compared to the 8 x 2.5 m spacing (149.2 kg/ha), with the former two

Table 4. Soil organic carbon and available nutrients in poplar plantation under different spacings after 6 years of planting

Spacings	Organic Carbon (g/kg)	Available N (kg/ha)	Available P (kg/ha)	Available K (kg/ha)
5 x 3 m	4.23	155.4	18.12	195.2
7 x 3 m, paired at 2.5 m	4.47	158.3	18.23	199.1
8 x 2.5 m	4.05	149.2	16.19	193.4
LSD ($p\leq0.05$)	0.19	5.37	0.72	3.36
Initial	3.22	136.2	13.72	188.4

being statistically equivalent. The higher available N concentrations in these spacings can be attributed to nitrogen release during organic matter mineralization, which is influenced by both litterfall and fine root biomass in the soil (Sharma *et al.*, 2015). Available phosphorus (P) and potassium (K) showed a similar trend. The 7 x 3 m (paired row) spacing had substantially higher levels of available P (18.23 kg/ha) and K (199.1 kg/ha) compared to the 8 x 2.5 m spacing. Dhaliwal *et al.* (2020) noted that in dense plantations, organic acids from roots can enhance phosphorus availability by activating it from the soil. Similarly, Lal *et al.* (2000) found that the organic decomposition process can solubilize potassium from insoluble forms found in soil minerals. Overall, the higher amounts of N, P, and K in the 7 x 3 m (paired row) spacing compared to the other two spacings are probably due to the increased litterfall and nutrient addition associated with this spacing configuration.

Overall, the availability of soil organic carbon (SOC), as well as accessible nitrogen (N), phosphorus (P), and potassium (K), increased by 31.9%, 13.3%, 27.6%, and 4.0%, respectively, from baseline levels. This enhancement is attributable to the addition of litterfall and the subsequent decomposition of plant material, which facilitates the conversion of dead organic matter into carbon dioxide (CO_2) and supplies essential nutrients. Sharma *et al.* (2015) observed an increase in SOC under poplar cultivation due to the addition and decomposition of litterfall. The incorporation of leaves alters the carbon-to-nitrogen (C: N) ratio of the soil, which in turn influences crop growth (Singh and Sharma, 2007). Nanda *et al.* (2021) noted that the improvement in accessible nutrient content following the harvest was linked to increased humus content resulting from litter decomposition in agroforestry systems. This process contributes to enhanced soil fertility and nutrient availability.

CONCLUSION

The study concludes that the diameter at breast height (DBH) and height of poplar plants were significantly greater in the 8 x 2.5 m spacing compared to the 5 x 3 m and 7 x 3 m (paired row) spacings after six years of growth. The quantity of litterfall and the return of nitrogen (N), phosphorus (P), and potassium (K) through litterfall during the 4th to 6th years were highest in the 7 x 3 m (paired row) spacing. Soil organic carbon (SOC) and available nutrients (N, P, and K) improved significantly from their initial levels, with the most pronounced enhancement observed in the 7 x 3 m (paired row) spacing. Incorporating poplar into cropping systems can effectively sustain soil health by increasing SOC and nutrient content through the addition of litterfall. This addition contributes to meeting some of the nutrient requirements of the agroforestry system, particularly given that poplars demand substantial nutrients throughout their growing period (March to October). Despite these benefits, further research is necessary to determine the precise contribution of litterfall nutrients to the overall nutrient needs of the agroforestry system. Understanding this contribution will be crucial for optimizing the sustainability and productivity of poplar-based agroforestry systems.

Authors' contribution

Conceptualization of research work and designing of experiments (BS, NK, RISG); Execution of field/lab experiments and data collection (BS, NK, RISG); Analysis of data and interpretation (BS, HK, SK, NK, RISG); Preparation of manuscript (BS, HK, SK, NK, RISG)

Conflicts of interest: Authors declare that they have no conflicts of interest.

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