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Litterfall dynamics and Soil Mesofaunal population as influenced by planting density in Sandalwood (*Santalum album* L.)

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Abstract

The present research was conducted from August 2022 to December 2023 at AICRP on Agroforestry field unit, ZARS, UAS, GKVK, Bengaluru. This study examined litterfall, litter nutrient content, decomposition rate, and soil mesofaunal populations under three planting densities (5 m x 5 m, 5 m x 4 m, and 5 m x 3 m) over a 17-month period. Litterfall followed a distinct seasonal pattern, peaking during March-May and declining during October-December, with wider spacing (5 m x 5 m) producing the highest cumulative litterfall (6854 kg ha⁻¹) compared to 5 m x 4 m (6567 kg ha⁻¹) and 5 m x 3 m (6255 kg ha⁻¹), attributable to greater crown development under reduced inter-tree competition. Nitrogen and phosphorus concentrations in litter were highest during active growth and post-monsoon periods and declined during senescence due to nutrient retranslocation, while potassium concentration was strongly influenced by leaching. Litter decomposition, assessed over two consecutive years, was fastest during the post-monsoon period (K = 0.08-0.09; half-life 7.7-8.6 months) and slowest during late winter (K = 0.03-0.04; half-life 17.3-23.0 months), reflecting the dominant role of soil moisture and temperature in regulating microbial activity. Soil mesofaunal abundance was consistently highest under 5 m x 5 m spacing across all three seasons with termites emerging as the dominant functional group throughout, followed by springtails and isopods. Overall, wider planting geometry enhanced litter production, nutrient return, and below-ground biological activity, indicating that spacing is a critical management factor governing nutrient cycling, decomposition dynamics and soil ecological stability in Sandalwood-based agroforestry systems under semi-arid conditions.

Keywords: Agroforestry, litterfall, litter decomposition, nutrient cycling, planting density, *Sandal*, soil mesofauna

Introduction

In India, distribution of genus *Santalum* in Western Ghats mainly in the dry regions of peninsular India stretched from Vidhya Mountains to the southwards, in the regions of Mysore and Tamil Nadu between 30°N and 40°S with a total extent of 9600 km² of which Karnataka (5245 km²) and Tamil Nadu (3040 km²) cover 8285 km² covers more than 90% of the total natural population of sandalwood in India (Chavan *et al.*, 2024) [3].

Litterfall constitutes one of the principal pathways through which organic matter and nutrients are transferred from the tree canopy to the soil in forestry and agroforestry systems. It represents an important component of ecosystem nutrient cycling by returning carbon, nitrogen, phosphorus, potassium and other essential elements to the forest floor. The quantity of litterfall produced varies with tree species, stand age, climatic conditions and seasonal patterns, making it a key indicator of ecosystem productivity. Likewise, the chemical composition of litter, including its carbon-to-nitrogen ratio, lignin content and concentrations of secondary metabolites, strongly influences decomposition rates and nutrient release. These characteristics determine the efficiency of microbial decomposition and nutrient mineralization, thereby affecting nutrient availability for plant growth. Continuous litter deposition also contributes significantly to the accumulation of soil organic carbon, improving soil structure, water-holding capacity and long-term soil fertility (Teramage *et al.*, 2024) [14].

Soil mesofauna are integral components of terrestrial ecosystems and play a vital role in the

decomposition of plant litter and the cycling of nutrients. These organisms mechanically fragment litter into smaller particles, increasing the surface area available for microbial colonization and accelerating the breakdown of organic matter. Through their feeding activities, burrowing behavior and interactions with soil microorganisms, soil mesofauna enhance nutrient mineralization, improve soil structure and contribute to the formation and stabilization of soil organic matter. Their abundance, diversity and community composition are strongly influenced by litter quantity and quality, soil moisture, temperature, vegetation type and management practices. Because they respond rapidly to changes in environmental conditions, soil mesofauna are widely recognized as reliable bio-indicators of soil health, ecosystem functioning, habitat quality, favorable microclimatic conditions that sustain diverse mesofaunal communities and support their ecological functions. Variations in tree species composition, planting density and litter characteristics can significantly influence the diversity and activity of soil mesofauna, thereby affecting decomposition rates and nutrient cycling (Remelli *et al.*, 2024; Angst *et al.*, 2024) ^[11, 1].

Materials and Methods

Experimental details

The present study was carried out at 'M' block, All India Coordinated Research Project on Agroforestry unit, Zonal Agricultural Research Station, GKVK, UAS, Bangalore, Karnataka from Aug 2022 to Dec 2024 situated in the Northern part of Bengaluru between 13° 08' North latitude and 77° 56' East longitude at an altitude of 925 m above mean sea level. The experiment containing three planting densities of Sandal conducted in strip plot design replicating three times. The trees were planted at 5 m x 5 m (400 plants/ ha), 5 m x 4 m (500 plants/ ha) and 5 m x 3 m (666 plants/ ha) spacing and study site was shown in Fig 1.

Litterfall quantification

Leaf litters of sandal wood and hosts were collected from agroforestry systems in an area of 1m x 1m using litter traps. The litters were collected at monthly interval. The collected leaf litters were washed, oven dried and then weighed. The recorded weight was added to quantify the accumulation of litters during the study period (Sundarapandian and Swamy, 1999) ^[12].

Litter decomposition pattern

The standard litter bag technique was employed for characterising litter decomposition rates. Twenty grams of leaf litter samples were packed into mesh bags (dimensions: 20 x 20 cm: 2 mm mesh size) and the bags were sealed. The bags were buried in the soil such that the contact is established with the soil. At monthly intervals, bags were retrieved from the soil and analysed in the laboratory. The bags were gently rinsed with water to remove the soil and other extraneous materials. The residual litter mass removed from the bags were oven dry at 80 °C and weighed to estimate the decomposition rate.

Rate of decomposition pattern

The litter decomposition rate was compared using litter decay rates, estimated with the commonly used first-order negative exponential decay model (Olson, 1963) ^[10],

$$X_t = X_0 e^{-kt}; k = -\ln(X_t - X_0)/t$$

Where X_0 and X_t are initial and final litter masses, respectively, and t is a time interval.

Half-life period ($T_{0.5}$)

The half-life period for each tree species i.e., the time required for the 50 per cent decomposition of the initial litter, was calculated by using the decomposition rate constant (k). (Olson, 1963) ^[10].

$$T_{0.5} = \log_e(0.50)/k$$

Nutrient analysis of litter

Preparation of samples

Samples were washed and oven dried at 60±2 °C. Then litter samples were powdered. The powdered samples were sieved and stored in air tight containers for further chemical analysis

Digestion of litter sample for other nutrient analysis

One gram of the powdered sample was digested with tri-acid digestion mixture (9:4:1 part of HNO_3 , H_2SO_4 and HClO_4). After completion of digestion, the volume was made up to 50 ml using distilled water. These solutions were used to estimate the following nutrients of the litter.

Nitrogen

One gram of the powdered sample was digested with concentrated H_2SO_4 and one gram of digestion mixture (100:20:1 part of K_2SO_4 , CuSO_4 and Selenium). Digested samples were transferred to the kjeldhal distillation unit using 4 per cent Boric acid, 40 per cent NaOH and 0.01N H_2SO_4 . Thus, estimated the nitrogen content (Jackson, 2005) ^[6].

Phosphorus

Venado molybdate yellow colour method was followed for phosphorus estimation. Two ml of the above digested aliquot was mixed with the venado molybdate reagent and the optical density (OD) was recorded at 420 nm using spectro photometer after standardization.

The OD was used to calculate the phosphorus concentration (Jackson, 2005) ^[6].

$$P(\%) = \frac{\text{Graph ppm} \times \text{Vol. of digested sample} \times \text{Vol. made up}}{10^6 \times \text{weight of sample} \times \text{Aliquot taken}} \times 100$$

Potassium

The flame photometric method was followed to estimate potassium concentration. The digested solutions were directly fed to the flame photometer after standardization (Jackson, 2005) ^[6].

$$K(\%) = \frac{\text{Graph ppm} \times \text{Vol. of digested sample} \times \text{Vol. made up}}{10^6 \times \text{weight of sample} \times \text{Aliquot taken for dilution}} \times 100$$

Statistical analysis

The experimental data generated during research was subjected to statistical analysis outlined by Gomez and Gomez (1984) ^[5]. The level of significance used in "F" test was at five per cent level of significance, this statistical procedure helped in identifying the significant effects of different treatments on the recorded parameters and ensured the reliability and validity of the experimental results.

Results and Discussion

Accumulated Litterfall of Sandal (August 2022 to December 2023)

Litterfall in Sandalwood exhibited a distinct seasonal pattern and varied moderately among the three planting densities evaluated in (Table 1). Across all spacing treatments, litter deposition was lowest during the post-monsoon to winter months (October-

December of both 2022 and 2023) and peaked during the summer months (March-May 2023). The maximum monthly litterfall was recorded in May 2023, with values of 675, 656, and 649 kg ha⁻¹ under 5 m x 5 m, 5 m x 4 m and 5 m x 3 m spacing, respectively. This seasonal peak is likely attributable to leaf senescence induced by moisture stress and natural canopy turnover characteristic of the late-winter to summer period.

The highest observation was under the widest spacing, 5 m x 5 m (6854 kg ha⁻¹), followed by 5 m x 4 m (6567 kg ha⁻¹) and 5 m x 3 m (6255 kg ha⁻¹) mean monthly litterfall followed the same ranking (403.17, 386.29 and 367.94 kg ha⁻¹, respectively). The greater litter output under wider spacing is attributable to superior crown development and higher per-tree leaf biomass resulting from reduced inter-tree competition for light, moisture, and nutrients. These results corroborate the findings of Nair *et al.* (2009) [9], who reported that canopy architecture and spacing are key determinants of litter dynamics in agroforestry systems.

In summary, sandalwood litterfall followed a marked seasonal rhythm, peaking during March-May, and both total and mean litterfall increased consistently with increasing spacing. These patterns underscore the role of planting geometry in regulating nutrient cycling and soil organic carbon inputs in sandalwood-based agroforestry systems.

Nutrient Content in Sandal Litter (August 2022 to December 2023)

Nitrogen concentration was generally higher during periods of active growth and immediately after the monsoon and lower during peak senescence (Table 2). For example, N content ranged from 1.15-1.82% in August 2022 but declined to 0.32-0.95% in January 2023, with a comparable decline observed in June 2023 (0.23-0.60%). This pattern is consistent with the retranslocation of nitrogen from senescing leaves prior to abscission, a physiological strategy common among perennial tree species (Nair *et al.*, 2009) [9]. Although the effect of spacing on N concentration was not uniform across months, litter from the 5 m x 5 m treatment recorded relatively higher N content in most sampling periods.

Phosphorus concentration ranged from approximately 1.08 to 1.98% and, similar to nitrogen, was higher during early growth and post-monsoon months and lower during peak litterfall, consistent with the pre-abscission retranslocation of this mobile nutrient. Variation among spacing treatments was narrow, suggesting a limited direct influence of planting density on litter P concentration. Litter quality and decomposition rate are closely linked to phosphorus cycling in agroforestry systems (Food and Agriculture Organization, 2018) [4].

Potassium concentration was consistently higher than that of N and P ranging from 0.66 to 3.99%, with the maximum recorded in July 2023 under 5 m x 5 m spacing and the minimum in March 2023. Because potassium is highly soluble and readily leached, its litter concentration is influenced strongly by rainfall and soil moisture in addition to physiological retranslocation.

Overall, spacing exerted a moderate rather than pronounced effect on litter nutrient concentration, with the 5 m x 5 m treatment generally recording marginally higher values, plausibly reflecting reduced root competition, more efficient nutrient uptake per tree and improved foliar physiological status. Closer spacing may have induced a nutrient dilution effect arising from greater inter-tree competition. Because total nutrient return to the soil depends on both litter nutrient concentration and litter quantity and the 5 m x 5 m treatment recorded both higher nutrient concentrations, cumulative nutrient return to the soil was likely greatest under this spacing.

Litter Decomposition Rate and Half-Life of Sandal Litter (2022-23)

The decomposition rate constant (K) and corresponding half-life ($t_{1/2}$) of sandalwood litter varied seasonally during 2022-23 (Table 3). The decomposition rate constant ranged from 0.04 to 0.09, with the highest value recorded in October (0.09), followed by December (0.08) and November (0.07); thereafter, K declined progressively from January (0.06) to March (0.04). The elevated decomposition observed during October–December likely reflects favourable soil moisture and moderate temperature conditions during the post-monsoon period, which promote microbial and enzymatic activity. The subsequent decline in K from January to March is consistent with reduced soil moisture and rising temperature, conditions known to constrain microbial biomass and decomposition efficiency (Lal, 2004) [7].

Litter half-life, representing the time required for 50% mass loss, varied inversely with K, ranging from 7.66 months in October to 17.25 months in March. This inverse relationship is consistent with the negative exponential decay model of litter decomposition (Olson, 1963) [10] and confirms that decomposition slowed progressively as the post-monsoon period gave way to drier winter and early-summer conditions.

The comparatively rapid decomposition and nutrient mineralization during the post-monsoon months indicate that nutrient release from sandalwood litter is seasonally synchronized with favourable moisture availability, whereas slower decomposition later in the season may result in temporary nutrient immobilization and greater short-term litter accumulation on the soil surface. Litter nitrogen content likely contributed to this seasonal decomposition pattern.

Litter Decomposition Rate and Half-Life of Sandal Litter (2023-24)

A broadly similar but somewhat more pronounced seasonal pattern was observed during 2023-24 (Table 4). The decomposition rate constant ranged from 0.03 to 0.08, being highest in October (0.08), intermediate in November and December (0.06 each), and lowest in February (0.03), with a slight recovery in March (0.04). As in the previous year, the elevated K value in October is attributable to favourable post-monsoon soil moisture and temperature conditions that support microbial proliferation and enzymatic breakdown of organic residues, whereas the decline through January–February reflects reduced soil moisture and cooler winter conditions that suppress microbial activity (Olson, 1963) [10].

Litter half-life ranged from 8.62 months in October to 23.0 months in February, with intermediate values in November–December (11.5 months) and similar values in January and March (17.25 months). The markedly extended half-life during winter indicates slower organic matter turnover and a greater potential for temporary nutrient immobilization within the litter layer, whereas the shorter half-life in October reflects more rapid nutrient mineralization and availability to sandalwood roots and associated intercrops.

Taken together, the two-year decomposition data indicate that decomposition was consistently highest during the post-monsoon period (October) and lowest during late winter, with half-life following the inverse trend in both years. Seasonal climatic variation, particularly moisture availability, thus emerges as the principal driver of litter mineralization and, by extension, of nutrient and carbon cycling in this sandalwood-based agroforestry system.

Soil Mesofaunal Population as Influenced by Planting Density: Kharif 2022

The abundance and composition of soil mesofauna in the sandalwood-based agroforestry system varied considerably with planting geometry during Kharif 2022 (Fig 2). Total mesofaunal population was highest under 5 m x 5 m spacing (62 individuals), followed by 5 m x 4 m (44 individuals) and 5 m x 3 m (35 individuals); the widest spacing supported approximately 77% more individuals than the closest spacing. This pattern suggests that reduced tree density favoured a more conducive soil microclimate, including greater litter accumulation, improved aeration, and enhanced moisture conservation, consistent with the ecological principles outlined by Swift *et al.* (1979)^[13] regarding the regulation of soil faunal abundance by litter quantity and quality.

Termites were the dominant taxon across all spacings (25, 21, and 18 individuals under 5 m x 5 m, 5 m x 4 m and 5 m x 3 m, respectively), reflecting their central role in lignocellulosic decomposition in tropical agroecosystems; their greater abundance under wider spacing likely reflects the higher availability of woody litter. Springtails (Collembola) and isopods were the next most abundant groups, particularly under 5 m x 5 m spacing (10 individuals each), consistent with their role as indicators of soil health through fragmentation of organic residues and stimulation of microbial activity (Brady and Weil, 2017)^[2].

Soil Mesofaunal Population as Influenced by Planting Density: Rabi 2022

During Rabi 2022, total mesofaunal population again followed the order 5 m x 5 m (27) > 5 m x 4 m (25) > 5 m x 3 m (17) (Fig 3), though overall abundance was lower across all spacings than in the preceding Kharif season, likely reflecting reduced soil moisture, slower litter decomposition and cooler temperatures characteristic of the Rabi season (Lavelle, 1997)^[8]. Termites remained the dominant taxon (11, 9, and 8 individuals under decreasing spacing, respectively), continuing to contribute substantially to organic matter breakdown despite the seasonal decline in overall abundance. Springtails, mites and Cryptostigmata (oribatid mites) were also consistently represented across treatments; mites showed comparatively greater representation under closer spacing during this season, possibly reflecting their tolerance of drier soil conditions.

Soil Mesofaunal Population as Influenced by Planting Density: Summer 2023

Total mesofaunal population during Summer 2023 ranged from 42 to 52 individuals, again highest under 5 m x 5 m spacing (52), closely followed by 5 m x 4 m (51), and lowest under 5 m x 3 m (42) (Fig 4). Despite the higher temperatures and lower soil moisture typical of summer, overall abundance remained higher than during Rabi and only marginally lower than Kharif, suggesting that the greater litter deposition, aeration, and canopy-mediated moisture retention associated with wider spacing buffered mesofaunal populations against seasonal moisture stress (Lavelle, 1997)^[8]. Termites again dominated across all spacings (a combined total of 73 individuals), reflecting their adaptation to drier conditions and continued role in lignocellulosic degradation, while mites showed their highest counts of the three seasons (14 individuals combined), indicating tolerance to fluctuating moisture regimes. Ants and Hymenoptera were more prominent under wider spacing, consistent with greater habitat heterogeneity.

Table 1: Accumulated litterfall of sandalwood (kg ha⁻¹) as influenced by planting density, August 2022 - December 2023

Month	5 m x 5 m	5 m x 4 m	5 m x 3 m
August 2022	388	379	360
September 2022	378	366	350
October 2022	278	265	254
November 2022	276	264	259
December 2022	269	256	245
January 2023	315	310	208
February 2023	373	362	325
March 2023	595	532	538
April 2023	646	612	602
May 2023	675	656	649
June 2023	578	548	518
July 2023	476	458	444
August 2023	394	385	368
September 2023	380	370	353
October 2023	281	270	265
November 2023	279	268	260
December 2023	273	266	257
Total	6854	6567	6255
Mean	403.17	386.29	367.94

Table 2: Nutrient content (%) in sandalwood litter as influenced by planting density, August 2022 -December 2023

Month	Nitrogen (%)			Phosphorus (%)			Potassium (%)		
	5 x 5 m	5 x 4 m	5 x 3 m	5 x 5 m	5 x 4 m	5 x 3 m	5 x 5 m	5 x 4 m	5 x 3 m
August 2022	1.25	1.15	1.82	1.95	1.87	1.54	3.27	2.89	2.19
September 2022	1.23	1.01	0.8	1.978	1.87	1.79	3.59	2.65	2.18
October 2022	1.31	0.77	0.5	1.6	1.56	1.23	2.08	2.52	2.14
November 2022	0.94	0.94	0.88	1.39	1.19	1.08	1.19	1.08	0.9
December 2022	0.86	0.53	0.16	1.89	1.75	1.57	2.92	2.37	2.1
January 2023	0.32	0.58	0.95	1.18	1.14	1.16	2.91	2.82	2.66
February 2023	1.07	1.01	0.81	1.96	1.55	1.25	3.22	2.97	2.7
March 2023	1.14	0.94	0.91	1.45	1.35	1.18	1.01	0.82	0.66
April 2023	0.95	0.87	0.54	1.94	1.9	1.78	2.21	2.19	2.07
May 2023	0.97	0.87	0.79	1.86	1.23	1.16	3.19	2.65	1.18
June 2023	0.6	0.56	0.23	1.32	1.18	1.15	2.98	2.52	2.14
July 2023	1.15	1.05	0.82	1.34	1.24	1.18	3.99	3.58	3
August 2023	1.28	1.21	1.9	1.66	1.93	1.66	3.32	2.97	2.25
September 2023	1.31	1.17	0.75	1.32	1.98	1.75	3.61	2.82	2.26
October 2023	1.35	1.15	0.55	1.69	1.64	1.38	2.21	2.59	2.19
November 2023	1.02	1.07	0.95	1.76	1.24	1.28	1.2	1.15	1.1
December 2023	0.9	0.59	0.46	1.95	1.88	1.59	2.99	2.52	2.14

Table 3: Litter decomposition rate constant (K) and half-life period of sandalwood litter, 2022–23

Month	Decomposition rate constant (K)	Half-life period (months)
October	0.09	7.66
November	0.07	9.85
December	0.08	8.62
January	0.06	11.5
February	0.05	13.8
March	0.04	17.25

Table 4: Litter decomposition rate constant (K) and half-life period of sandalwood litter, 2023-24

Month	Decomposition rate constant (K)	Half-life period (months)
October	0.08	8.62
November	0.06	11.5
December	0.06	11.5
January	0.04	17.25
February	0.03	23
March	0.04	17.25

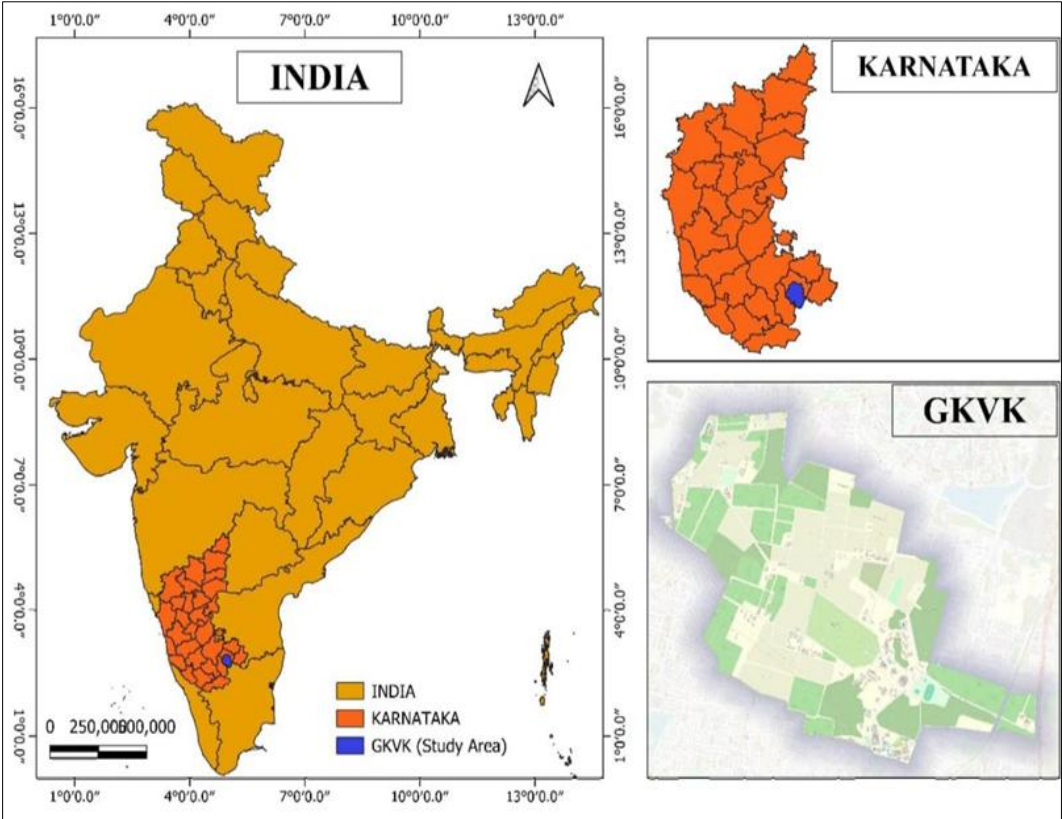


Fig 1: Study site of Litter dynamics in Sandalwood in M block, GVKK,Bangalore

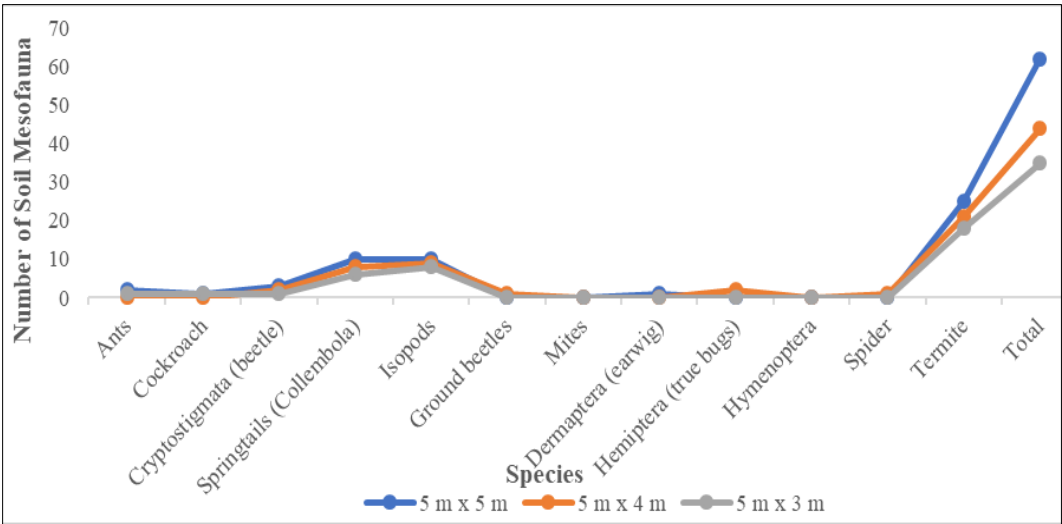


Fig 2: Soil mesofaunal population in the sandalwood-based agroforestry system as influenced by planting density, Kharif 2022

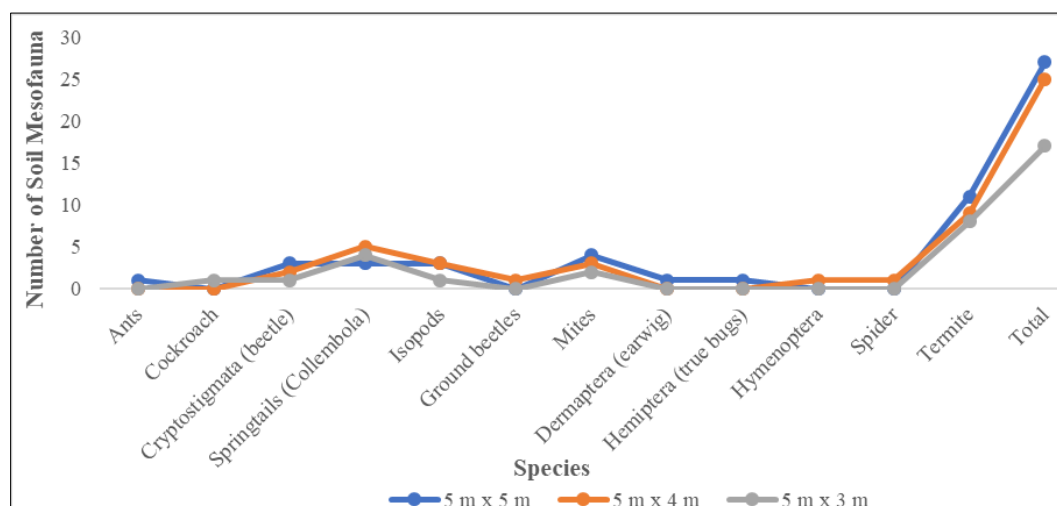


Fig 3: Soil mesofaunal population in the sandalwood-based agroforestry system as influenced by planting density, Rabi 2022

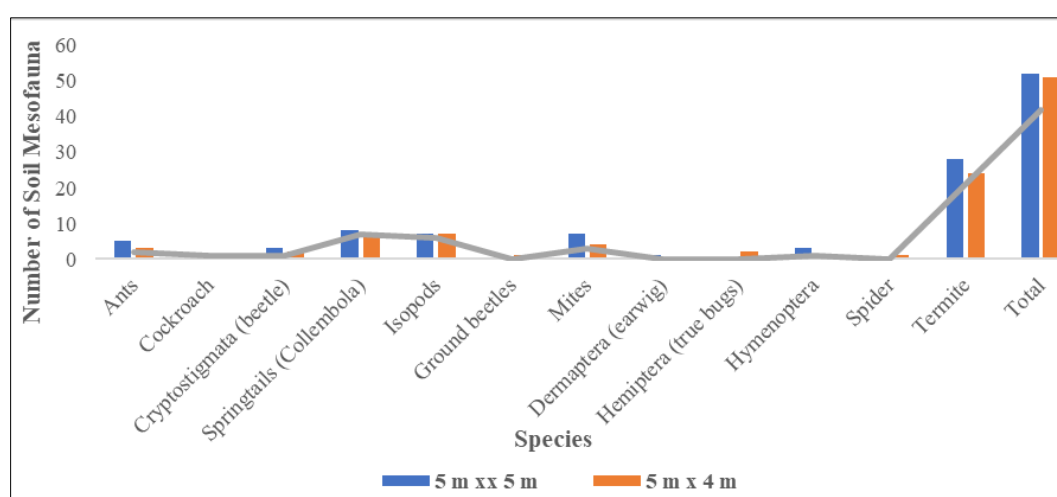


Fig 4: Soil mesofaunal population in the Sandalwood-based agroforestry system as influenced by planting density, Summer 2023

Conclusion

Across all three seasons, soil mesofaunal abundance followed the consistent order $5\text{ m} \times 5\text{ m} > 5\text{ m} \times 4\text{ m} > 5\text{ m} \times 3\text{ m}$, while the seasonal trend followed Kharif > Summer > Rabi. Termites were the dominant functional group in every season, followed by springtails and isopods. These consistent patterns indicate that wider planting geometry enhances below-ground biodiversity and soil ecological stability in Sandalwood-based agroforestry systems, most plausibly through its effects on litter deposition, soil aeration and moisture retention, and highlight the importance of optimal planting density for long-term soil biological sustainability under semi-arid conditions.

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Authors' contributions

HM carried out experiment, collected the data, analysed and writing the original manuscript, HDC conceptualized the experimental study, helping in designing, edition and supervision and PKMB, RAR and SMA helped in field experiment and edited the manuscript. All authors read and approved the manuscript.

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