LITTER DYNAMICS AND SOIL CHANGES UNDER SIX-YEAR-OLD BAMBOO STANDS

by

VIJAY KUMAR

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THESIS

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VELLANIKKARA

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DECLARATION

I, hereby declare that this thesis entitled **"Litter dynamics and soil changes under six-year-old bamboo stands"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

Vijay Kumar

Vellanikkara

Vijay Kumar

Date: 19/12/2023

(2021-17-011)

CERTIFICATE

Certified that this thesis entitled "**Litter dynamics and soil changes under six-year-old bamboo stands**" is a record of research work done independently by Mr. Vijay Kumar (2021-17-011) under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship, or associateship to him.

Vellanikkara

Date: 19/12/2023

Dr. V. Jamaludheen
(Major Advisor, Advisory Committee)
Professor and Office in charge
AICRP on Agroforestry
Department of Silviculture and Agroforestry
College of Forestry, Vellanikkara

CERTIFICATE

We, the undersigned members of advisory committee of Mr. Vijay Kumar (2021-17-011) a candidate for the degree of **Master of Science in Forestry** with major in Silviculture and Agroforestry, agree that this thesis entitled **"Litter dynamics and soil changes under six-year-old bamboo stands"** may be submitted by Mr. Vijay Kumar, in partial fulfilment of requirement for the degree.

Dr. V. Jamaludheen
(Major Advisor, Advisory Committee)
Professor and Office in charge
AICRP on Agroforestry
Department of Silviculture and Agroforestry
College of Forestry
Kerala Agricultural University
Vellanikkara, Thrissur

Dr. T.K Kunhamu
(Member, Advisory Committee)
Professor and Head
Dept. of Silviculture and Agroforestry
College of Forestry
Kerala Agricultural University
Vellanikkara, Thrissur

Dr. Divya Vijayan V.
(Member, Advisory Committee)
Assistant Professor (SS & AC)
Department of Remote Sensing &
Geographic Information System
College of Forestry
Kerala Agricultural University
Vellanikkara, Thrissur

Dr. K. Surendra Gopal
(Member, Advisory Committee)
Department of Agricultural Microbiology
College of Agriculture
Kerala Agricultural University
Vellanikkara, Thrissur

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

Introduction

1. INTRODUCTION

Bamboos are monocotyledonous perennial grasses belonging to the sub-family Bambusoidae of the family Poaceae (Gramineae), characterized by rapid growth, woody culms, robust underground rhizome system, and infrequent flowering. Bamboos are widely distributed in tropical and subtropical regions around the world and are considered one of the most sustainable forest resources. Globally, bamboo covers an extensive area of more than 37 million hectares, accounting for approximately 3.2% of the forested areas in their respective countries or about 1% of the world's total forested area (Lobovikov *et al.,* 2007). India is endowed with abundant resources and species diversity of bamboos ranking second only to China. India is home to approximately 125 native bamboo species and 11 exotic ones belonging to 23 genera, both in the wild and on farms, covering 15.0 million hectares with a standing stock of 189 million tons (Kaushal *et al*., 2021a). Over 50% of the bamboo species naturally occurring in India are endemic to the country.

Bamboo plays a crucial role in the livelihoods of 2.5 billion people globally, and in India, approximately 2 million traditional artisans or farmers rely on bamboo for their income. To further ensure that farmers receive the benefits, the Indian government, in 2017, amended section 2(7) of the Indian Forest Act 1927 to exclude bamboo grown outside forest areas from the definition tree (FSI,2021).

Bamboo, as an annual crop with versatile uses, holds significant potential for alleviating poverty, protecting the environment, and supporting the achievement of various United Nations Sustainable Development Goals (SDGs), including SDG1, SDG7, SDG11, SDG12, SDG13, SDG15, and SDG17 (INBAR, 2023). Bamboo also has a significantly higher potential for accumulating biomass compared to many fast-growing exotic tree species (Devi and Singh, 2021). Its extensive root system plays a crucial role in soil binding and can help raise the water table, making it a valuable component in global anti-desertification efforts and thus contributes to the Bonn Challenge (Kaushal *et al*., 2020). Bamboo also has the potential to contribute to India's NDC’s (Nationally Determined Contribution) commitments, specifically in the goal of creating an additional carbon sink of 2.5–3 GtCO_2e through increased forest and tree cover by 2030.

According to FSI (2021) report, the total area under bamboo in the country has decreased by 1.06 million hectares. In response to this, the Government of India (GOI) has allocated a budget of Rs. 12.90 billion (equivalent to $177.6 million) to promote the bamboo sector over the next two years. This initiative aims to bring around 0.1 million hectares of land under bamboo cultivation in both forested and farmland areas. The goal is to enhance agricultural productivity, create livelihood opportunities, meet the demand from industries, and reduce the pressure on existing forests (Kaushal *et al*., 2021b). Additionally, the Government of India has introduced the National Bamboo Mission, which primarily focuses on encouraging the cultivation of high-quality bamboo species. This initiative aims to increase bamboo cultivation in both forested and non-forested areas, with the aim of revitalizing rural economies and doubling farmer's incomes(NBM, 2019).

Bamboo plays a major role in ecosystem dynamics. Bamboos are well-known for improving soil health and nutrient condition by adding their aboveground and belowground litter. Soil particularly of perennial vegetation like bamboo have higher organic matter and is thus considered an essential terrestrial carbon sink (Kumar *et al.,* 2022). The process of litterfall, where bamboo sheds plant material, is a pivotal mechanism in regulating nutrient cycling, primary productivity, soil health and indirectly affecting the soil microbial community. In turn, the soil microbes regulate the availability of plant nutrients through the mineralization of soil organic matter and solubilization of soil minerals. The decomposition process releases nutrients essential for plant growth and development (Chakravarty *et al.,*2020). Nutrient uptake by plants and its return to the soil through the litter, in turn, influences physico-chemical properties of the soil (Rawat *et al.,* 2010). Thus, the process of litter decomposition is undeniably critical for maintaining site fertility and productivity (Prescot, 2005).

Kerala is recognized as a significant biodiversity hub for bamboo species. The state is home to 28 different bamboo species, covering an extensive area of

0.24 million hectares. Interestingly, the majority of bamboo extraction in Kerala, approximately 67.3%, is sourced from homegardens (KSBM,2022). However, despite this rich biodiversity, the total availability of bamboo and reed from both forests and homesteads only amounts to 0.304 million tonnes, falling short of the required 0.62 million tonnes. This indicates a significant gap between the supply and demand, with supply meeting only about 50% of the required amount(KFRI, 2009). It's important to note that even though there is a substantial gap between the demand and supply of bamboo, the depth of traditional knowledge among Kerala's farmers regarding bamboo cultivation is often thought to be sufficient. However, there is a lack of comprehensive documentation of this knowledge in existing literature. Claims about the effectiveness of this traditional knowledge have been made without rigorous analysis and are mostly based on assumptions (Kumar, 1997). It's important to note that Kerala farmers typically have knowledge about a specific type of bamboo called *Bambusa bambos*, which is the most found bamboo species in the state (KFRI, 2009). Although, there exists a variety of bamboo species that offer high economic returns to the farmer and offer numerous ecological benefits. But the growth performance varies from species to species and growing conditions such as climatic, edaphic, and management practices. These variations are species-specific as well as site-specific. Similar species growing in different site conditions may perform differently, and its effect on microclimate is also considerable.

In the humid tropical climate of Kerala, there is a significant lack of information regarding the growth performance of economically important bamboo species that have been designated as priority species by INBAR, and how they affect the physicochemical properties of soil. Also, there is a little or no information available on litter production, decomposition rates, and mineralization rates for these bamboo species within this specific climatic context. Given that the dynamics of litter significantly impact the net primary productivity of ecosystems, understanding these processes is crucial for assessing the nutrient balance within an ecosystem (Thomas *et al.*, 2014).

In this background, a detailed study was undertaken on six priority species of economical bamboo viz. *Bambusa vulgaris* Schrad, *Bambusa balcooa* Roxb*.*, *Bambusa tulda* Roxb*.*, *Dendrocalamus brandisii* (Munro) Kurz*.*, *Dendrocalamus asper* (Schult.f.) Back.ex Heyne and*, Dendrocalamus longispathus* Kurz. with the objective to quantify litter and nutrient turnover under selected bamboo species in the humid tropical region of central Kerala. The study will also probe into assessing the soil physico-chemical and biological changes under these selected bamboo species.

Review of literature

2. REVIEW OF LITERATURE

Bamboo is the fastest growing and most versatile plant on the planet. For centuries, it has been a crucial part of the daily lives of millions of people in tropical countries (Liese and Köhl, 2015). Bamboo, like rice, wheat and maize is another significant grass that is closely interlinked to human sustenance. It serves various purposes such as providing shelter, food, paper, and more(Clark *et al.,* 2015). Beyond its socioeconomic advantages, bamboo plays a crucial role in diverse ecosystems. The extensive root systems of bamboo help bind soils and elevate the water table, thus contributing significantly to global anti-desertification initiatives. (INBAR, 2023). Its versatility is unparalleled in the plant kingdom, earning it the moniker "the plant of a thousand uses." The relevant literatures related to different parameters studied for the title "Litter dynamics and soil changes under six-year-old bamboo stands" is presented in this chapter.

2.1. Bamboo Diversity and Distribution:

Bamboos are perennial woody grass that belongs to the Poaceae (Gramineae) family and falls under the subfamily Bambusoideae. It encompasses a vast range of around 121 genera with over 1662 species (Canavan *et al.,* 2017). Naturally, bamboo is distributed across tropical and subtropical regions, spanning from approximately 46° N to 47° S latitude. It is commonly found in continents like Africa, Asia, and Central and South America. Certain species can even thrive in the relatively milder temperate zones of Europe and North America(Lobovikov *et al.,* 2007). The natural distribution of different bamboo species across various regions relies on specific factors like soil type, rainfall, temperature, and altitude. Bamboo grasses grow naturally in areas receiving an annual rainfall ranging from 1200 to 4000 mm, and an average yearly temperature of 8 to 36 °C. They also thrive in different soil types, ranging from fertile alluvium to compact lateritic soils, loamy soil, and sandy soils(Akinlabi *et al.,* 2017). As a result, bamboo is commonly found in regions with moderately moist to wet forest environments, whether in temperate or tropical zones. Nevertheless, certain bamboo species have been observed to thrive in open grasslands or more confined habitats(Ahmad *et al.,* 2021).

The bamboo plant is present worldwide across all continents except Europe and Antarctica. However, a few years ago, some species were introduced to Europe(Akinlabi *et al.,* 2017). Whereas in Asia, bamboo exhibits its highest diversity, comprising approximately 50 genera and 900 species, making up 75% of the global total. China leads in species diversity with around 600 species, followed by India (135) and Japan (84). Asia's bamboo-covered land encompasses approximately 25 -30 million hm^2 area; India occupies the top spot with roughly 15 million hm^2 area, while China holds around 6.4 million hm^2. Other nations like Myanmar, Indonesia, Malaysia, Vietnam, and more collectively account for around 10 million hm^2. In the America, there are 21 genera and 345 species, concentrated mainly in Latin America, with a small presence in the south-eastern United States. Whereas Africa recognizes about 13 genera and 40 species, primarily distributed in East African countries including Tanzania, Kenya, Zambia, Ghana, Ethiopia, Uganda, Mozambique, and Madagascar (Ahmad *et al*., 2021).

2.2. Diversity of Bamboos in India:

Bamboos in India exhibit considerable diversity in both their habitats and growth patterns. India holds the position of the second most biodiverse country in terms of bamboo following China, housing 136 species comprising 125 native and 11 exotic species (NBM,2019). In India, bamboo can be found across various types of forests, ranging from tropical to sub-alpine regions. Some bamboo species are exclusively cultivated in specific locations. In India, bamboos thrive naturally in nearly all states except for the Kashmir region in Jammu and Kashmir. The majority, around 70% of bamboo species in India, are concentrated in the eight Sister States of North-east India and the Western Ghats. These bamboos stretch from the southern coastal plains and extend to altitudes as high as 3700 m in the Himalayas. Approximately, the forest area covered by bamboo in India was estimated to be about 15 million hectares, constituting nearly 12.8% of the country's total forested area (Sharma and Nirmala, 2015).

In India, three prominent bamboo genera, namely Bambusa, Dendrocalamus, and Ochlandra, stands out, each comprising more than 10 species.

Among these, Bambusa (with 37 species and 2 varieties) and Dendrocalamus (with 18 species) thrive across diverse regions and habitats. On the other hand, the third genus, Ochlandra (with 11 species and 1 variety), is mainly confined to South India. Collectively, these three genera account for approximately 45% of the entire bamboo species catalogued in India(Tewari *et al*., 2019).

Although bamboo's natural growth spans across every state, the extent of its presence varies significantly due to differing climatic conditions. The distribution of bamboo species in different Indian states indicates that *Bambusa spp*. and *D. strictus* prominently inhabit Himachal Pradesh, Madhya Pradesh, and Maharashtra. Conversely, *B. arundinacea* and *D. strictus* are the predominant species in Andhra Pradesh, Bihar, Jharkhand, and Uttar Pradesh. *Dendrocalamus strictus* and *Bambusa bambos* thrive in sub-Himalayan and Siwalik regions. Species like *Drepanostachyum falcatum* (locally known as Ghal Ringal), *Himalayacalamus falconeri* (known as Deo Ringal), *Thamnocalamus spathiflorus* (referred to as Thaam Ringal), and *Thamnocalamus jaunsarensis* (known as Jamura Ringal) flourish on the slopes of hills, forming a natural belt in the higher altitudes of Himachal Pradesh and Uttarakhand(Negi *et al.,* 2022)**.** Indeed, it is a well-established fact that bamboo typically thrives in regions with substantial rainfall ranging from approximately 1200 mm to 6350 mm. However, there are exceptions such as the species *Dendrocalamus strictus*, can be found even in the comparatively arid regions of Rajasthan(Tewari *et al*., 2019).

2.3. Diversity of Bamboos in Kerala:

The Kerala region of the Western Ghats stands out as a significant hub of bamboo diversity, ranked second next to Arunachal Pradesh. Currently, a total of 25 bamboo species belonging to seven genera have been documented in Kerala. This constitutes roughly 24% of the total bamboo diversity across India and an impressive 95% of the bamboo species reported from the peninsular region of India (Kumar and Ramesh, 2000).

Bamboos occurs as an important associate in various ecosystems, including southern hilltops, tropical evergreen forests, moist teak-bearing forests, as well as dry bamboo and reed breaks. *Bambusa bambos*, *Dendrocalamus strictus, Ochlandra travancorica*, and *O. scriptoria* are extensively distributed with in the state. The most prominent bamboo species in Kerala is *B. bambos*, thriving in the moist deciduous forests with an average rainfall of 1200-2000 mm and temperatures ranging from 18 to 33°C. *Ochlandra travancorica* holds immense importance in tropical evergreen forests, displaying optimal growth in highly wet evergreen environments. Notably, two shrubby bamboo species, *Sinarundinaria debilis* and *S. hirsuta,* have been identified for the first time within the confines of the Silent Valley National Park. Additionally, the Ranni Forest Division of Pathanamthitta District has reported the presence of seven distinct species of *Ochlandra* (KFRI, 2009).

In the state of Kerala, bamboo is sourced from both forested areas and homesteads, whereas reed primarily sourced from forested regions. KSBM (2022), homegardens produce 67.3% and forest 32.7% of Kerala total supply of bamboos. Bamboo, including reed bamboo, serves as a primary resource for both the pulp and paper industry, as well as traditional sectors within the state. There are six species of bamboo, that are prevalent in homesteads. Among these, *Bambusa bambos* makes up the majority at 96%, followed by *Bambusa vulgaris* at 2.23% (Muraleedharan *et al*., 2007).

2.4. Bamboo morphology and growth attributes:

A bamboo plant is composed of several components, including roots, rhizome, culm (stem), branches, flowers, and fruits. The roots are fibrous and create a dense interconnected network within the soil(Akinlabi *et al.,* 2017). Rhizomes contain buds that mature into shoots, which then emerge from the soil to establish a cluster of culms. According to the branching pattern, there are generally three types of rhizomes that have been documented: 1) pachymorph (also known as sympodial or clump-forming), 2) leptomorph (referred to as monopodial, runner, or walking bamboo), and 3) amphimorph (which is a mixed type, exhibiting characteristics of both pachymorph and leptomorph) (Stapleton, 1997; Judziewicz *et al.*, 1999).

The culm of a bamboo plant has a cylindrical shape and is partitioned into segments by nodes or diaphragms. The region between two nodes along the culm is referred to as an internode(Amada and Untao, 2001). Bamboo culms are different because they don't have regular bark like many other plants. Instead, they have a smooth and strong outer covering made up of silica. These culms also have branches and lots of leaves. What sets various bamboo species apart is their diverse growth patterns when it comes to the development of these culms.(Ahmad *et al*., 2021).

Bamboo buds and protective coverings called sheaths develop and appear from the node area. Bamboo exhibits various types of sheath coverings, including those for the stem (culm), leaves, branches, and the underground stem (rhizome). However, the most prominent among these are the sheaths that encase the stem, specifically known as culm sheaths.

Bamboos follow an exponential growth pattern, which means that every year, a new batch of shoots grows from the base of the bamboo cluster right after the monsoon rains (Ueda, 1960). A young stem, known as a culm, reaches its full height in just 2 to 4 months. This quick growth happens because each part of the stem stretches out like a telescope, and it also becomes wider. As time goes on, the stem becomes tougher through a process called lignification (McClure, 1966). Following their emergence, culms require approximately 3 to 4 years to reach maturity before they are ready for harvesting.

In contrast to most other plants, bamboo possesses a unique flowering cycle. There are typically four types of flowering patterns observed in bamboo: sporadic flowering, massive synchronized flowering, a combination of massive synchronized and sporadic flowering, and partial flowering(McClure, 1966). Sporadic flowering in bamboo can be triggered by environmental factors like drought or cold rather than genetics. Flowering is limited to individual stems (culms) within the same clump in a forest or a specific plant group within an area. On the other hand, massive synchronized flowering, also known as gregarious flowering, is characterized by more than half (>50%) of a bamboo population in an area flowering together. In cases of combined massive synchronized and sporadic flowering, some species might experience sporadic or small-scale flowering before or after larger sections of bamboo population go through flowering. Partial flowering, occurring between sporadic and massive synchronized flowering, is characterized by scattered instances of flowering rather than uniform occurrence. It tends to happen in patches across the population(Zheng *et al*., 2020). The patterns and timing of flowering vary among different bamboo species.

2.5. Bamboo growth patterns:

Bamboo is a plant species known for its rapid growth. When provided with ideal conditions, some species of bamboo has the capacity to achieve a growth rate of up to two inches per hour, enabling it to attain a towering height of 60 feet within a mere 3-month period (Abdul Khalil *et al.,* 2012). Gaikwad *et al.* (2021) conducted a field experiment involving seven distinct bamboo species, two years after their plantation in the semi-arid climate of Maharashtra's Entisol. These seven bamboo species were used as treatments with three replications each. Their findings indicated that *Bambusa tulda* displayed the highest number of culms per clump (59.32), culm density (49413.56 culms ha^{-1}), new culms per clump (13.80), and clump girth (717.27 cm). On the other hand, *Dendrocalamus strictus* showcased the highest culm height (6.39 m), basal culm diameter (8.16 cm), diameter at breast height (7.13 cm), culm girth at the 5th internode (16.53 cm), and internodal length (27.51 cm). *Bambusa bambos*, in turn, recorded the highest number of internodes per culm (28.34). The outcomes of this study led them to conclude that the bamboo species subjected to testing exhibited significant differences in growth-associated attributes amongst themselves.

Lal *et al.* (2022) conducted a study at Indira Gandhi Krishi Vishwavidyalaya in Raipur, Chhattisgarh. They examined a *D. strictus* bamboo plantation (8×6 m spacing) by recording bamboo parameters at eight-month intervals (July 2018 and

March 2019). The average culms per bamboo clump increased from 33.38 to 45.0, with the total culms per hectare growing from 6953.01 to 9374.85 (25.83% new culm growth). Clump diameter increased from 4.68m to 5.66m (20.94% increase), while the average third internodal diameter grew from 3.34cm to 3.56cm (6.59% increase). Culm height also rose from 7.27 ± 1.28m to 8.35 ± 0.54m, a 1.08m (14.86%) gain. Also, there were no new culms emerging from November to March.

Seethalakshmi *et al*. (2009) conducted a comparative study in which bamboo productivity was compared with that of other important woody species such as teak, eucalyptus, babul, casuarina, and silver oak. The results revealed that bamboo outperformed the others in terms of biomass production. For example, *Bambusa bambos* exhibited a biomass production of 280 Mg ha^{-1} by the age of 8 years. In comparison, woody species like teak and eucalyptus showed corresponding values of 40 Mg ha^{-1} and 285 Mg ha^{-1} at the age of 10 years respectively, within short timespan using minimum resources.

A study conducted by Getahun *et al*., 2023 in the Guangua district of Ethiopia to evaluate the growth and potential biomass production of five exotic bamboo species. The growth performance, encompassing culm production, culm height, internode length, and biomass production, exhibited significant variations among the species. *D. asper* and *D. hamiltonii* displayed superior growth and biomass production. Notably, *D. asper* showcased the highest average culm height (802.1 ± 223.1 cm), mean diameter at breast height (DBH) (46.8 ± 10.3 mm), and mean internode length (32.1 ± 1.5 cm). The study recommended the inclusion of *D. asper* and *D. hamiltonii* as potential species for tree planting initiatives within Ethiopia.

Kumari and Bhardwaj (2019) conducted a comparative investigation aimed at assessing the biomass production across seven bamboo species. Notably, all the bamboo species exhibited significant variations in terms of growth performance. The species that demonstrated the highest growth parameter values was *Dendrocalamus hamiltonii*, with a diameter of 6.33 cm and a height of 9.35 meters. Following closely was *Dendrocalamus strictus*, with a diameter of 6.06 cm and a height of 8.59 m. Conversely, the species *Phyllostachys aurea* exhibited the least values in terms of growth parameters, having a diameter of 1.70 cm and a height of 3.15 m.

Amani *et al*. (2022) conducted a field trial with the purpose of evaluating the growth performance of six bamboo species that hold potential significance within the humid tracts of Kerala. The outcomes from the field trial revealed notable disparities in growth and productivity among the six bamboo species. *Bambusa vulgaris, Dendrocalamus brandisii,* and *D. longispathus* exhibited a superior overall growth performance. For instance, *B. vulgaris* and *D. brandisii* attained the highest clump heights (14 ± 1.3 m and 12.92 ± 2.13 m, respectively), clump circumferences (5.8 ± 1.2 m and 6.01 ± 1.3 m, respectively), and clump girths (16.4 ± 2.3 cm and 18.2 ± 2.1 cm, respectively). On the other hand, the maximum internodal length was observed in *D. brandisii* (44.64 ± 5.16 cm) and *D. longispathus* (36.23 ± 5.38 cm).

Amlani *et al.* (2017) did an experiment using RBD at Gujrat to assess the variation in the growth of 15 species of bamboo. The fifteen bamboo species were used as treatments with three replications. They reported that among growth parameter maximum value for culm diameter at breast height found in *Bambusa bambos* (7.75 cm); culm height (17.73 m) and clump height (18.80 m) in *Bambusa vulgaris* (Green); internodal length in *Bambusa polymorpha* (86.25 cm). They found the definite variation for growth parameters among different species of bamboos.

Alemayehu *et al.* (2015) evaluated the growth performances and biomass accumulation of four introduced bamboo species at Jimma Agricultural Research Centre. *D. hamiltonii* showed the best performance with average DBH, height and basal area 3.44+0.213 cm, 10.58+0.47 m, and 9.71+1.25 cm respectively. Among the four species *D. hamiltonii* showed the highest total biomass accumulation of 82.16+0.94 kg/clump. The result of study showed that *D. hamiltonii* and *D. membranaceus* are good potential bamboo species for cultivation in Ethiopia.

In their study, Kittur *et al.* (2017) investigated the growth performance of *D. strictus* under varying spacings of 12×12, 10×10, 8×8, 6×6, and 4×4 meters. The spacing of 12×12 meters resulted in the highest recorded metrics for culms per clump (130), clump diameter (1.58 m), and crown width (8.13 m), while the 4x4 meter spacing yielded the lowest figures of 47.66, 4.69 m, and 1.03 m, respectively. The findings indicated that closer spacing contributed to greater clump heights, while more spaced-out bamboo led to larger crown widths and clump diameters. In comparison to the closest spacing (4×4 meters), the widest spacing (12×12 meters) exhibited a 30% reduction in clump height and a 52% increase in culm diameter.

Kaushal *et al.* (2021c) documented the growth progress of *Dendrocalamus stocksii* following its introduction in the Himalayan foothills. Enhancements in bamboo attributes were observed as follows: The number of new culms per clump increased from 6.44 (in 2013) to 8.25 (in 2019); culm diameter expanded from 2.40 cm (in 2013) to 4.85 cm (in 2019); culm height increased from 3.7 meters (in 2013) to 9.8 meters (in 2019). Furthermore, the internode length increased from 21.7 cm in 2013 to 35.7 cm in 2017, after which it showed a decline.

2.6. Litter Dynamics

In ecological context, the term "litter" holds two interpretations: it refers to the layer of dead plant material covering the soil surface, as well as to plant material that has become detached from a living plant (Krishna and Mohan, 2017). Leaf litter accumulation and subsequent decomposition are vital processes that facilitate the cycling of organic materials and nutrients in tropical forest ecosystems(Wieder and Wright, 1995). Plant litter functions as both a temporary sink and a gradual slow supplier of nutrients(White *et al.,* 1988), guaranteeing sustained nutrient enrichment in the soil over the long term(Cuevas and Medina, 1988). Studying the litter dynamics is notably significant for effectively managing the nutritional aspects within tropical ecosystems. As these environments mostly depend on the recycling of nutrients present in plant debris to sustain vegetation, which in turn has an indirect impact on primary production(Li-Hua *et al.,* 2014). While there exists an abundance of literature concerning studies on litter dynamics in tropical regions, there is a limited amount of research in this area specifically focused on bamboo forests, particularly at the level of plantations. The existing literature in this regard is examined in the following section.

2.6.1. Rate of litter production and its seasonal fluctuation:

Litter production refers to the process of shedding vegetative and reproductive components due to factors like senescence, stress, mechanical forces (such as wind and rainfall) or by combination of these influences(Kozlowski, 1973).Litter production plays a significant role in understanding ecosystem functioning, specifically its connection to processes like the incorporation of soil organic carbon, the dynamics of decomposition, and the cycling of nutrients(Giweta, 2020). The rate of litter production displays substantial diversity across various global ecosystems. Leaves constitute a significant portion, accounting for 70 - 85% of the overall litter production, whereas the contributions of woody and reproductive litter differ based on the species composition. Certain studies have observed pronounced seasonal fluctuations in litter production patterns, which can be attributed to variations in rainfall and temperature throughout different seasons(Descheemaeker *et al.*, 2006).

Li-Hua *et al.* (2014) conducted a study to assess the litterfall production of two subtropical bamboo plantations in China: *Pleioblastus amarus* (referred to as "P stand") and a hybrid bamboo, *Bambusa pervariabilis* × *Dendrocalamopsis daii* (referred to as "H stand"). Their findings unveiled that the average annual aboveground litter production was 494 g m^{-2} $year^{-1}$ and 434 g m^{-2} $year^{-1}$ for the P and H stand, respectively. Leaf litter made up the bulk (around 80%) of the litter production in both stands, followed by twigs (∼10%) and sheathes (∼9%). The overall mass of aboveground litterfall exhibited a pronounced seasonal pattern, with the peak of leaf litterfall occurring in May for both stands. Notably, between March and July, around 69% of the total aboveground litterfall in the P stand and 81% in the H stand took place.

Upadhyaya *et al*. (2008) conducted a study to assess the litter biomass of four major bamboo species across different altitudinal ranges in Arunachal Pradesh. The results indicated that bamboo species at higher altitudes exhibited greater foliage biomass compared to those at lower elevations. The annual litter biomass, in descending order, was recorded as follows: *Bambusa balcooa* > *Bambusa pallida* > *Phyllostachys bambusoides* > *Arundinaria racemosa*, with values of 24.2, 15.3, 5.68, and 1.76 t $ha^{-1}yr^{-1}$ respectively. However, it's worth noting that the percentage of litter contributing to the total aboveground biomass was higher in *A. racemosa* (9.79%), while it was comparatively lower in *B. balcooa* (6.41%).

In their study, Kuruvilla *et al.* (2016) documented the behaviour of litter production, decomposition, and nutrient release dynamics in *Munrochloa ritcheyi* endemic bamboo of the Western Ghats. The study determined that the overall annual litter production amounted to 2.842 metric tons per hectare per year. The litter production exhibited triphasic pattern, with a prominent peak occurring in February 2012 and two minor peaks observed in May and December 2011. The study's findings also revealed that the reduction in nitrogen (N) and potassium (K) content during the decomposition of litter was continuous, while phosphorus (P), calcium (Ca), and magnesium (Mg) showed temporary accumulation stages before their eventual release. The order of nutrient release from the decomposing litter was as follows: N = Mg > K = Ca > P.

Kaushal *et al.* (2020) studied bamboo litter production in the Western Himalayas with a 4×5 meter spacing. The outcomes of the study revealed that *Bambusa vulgaris* had higher litter fall in 2015 and 2016 (2.94 and 6.04 Mg ha^{-1}), while *Bambusa nutans* had lower litter fall (1.81 and 1.79 Mg ha^{-1}). In 2017, *Dendrocalamus hamiltonii* had the highest litter fall (12.4 Mg ha^{-1}), followed by *B. vulgaris* (12.1Mg ha^{-1}), *B. balcooa* (11.5 Mg ha^{-1}), *D. strictus* (10.7 Mg ha^{-1}), *B. nutans* (9.7 Mg ha^{-1}) and *B. bambos* (8.9 Mg ha^{-1}). The study's findings concluded that there is a positive correlation between the age of the plantation and the quantity of litter fall.

Jijeesh and Seethalakshmi (2015) conducted a study on the litter dynamics of the introduced *Bambusa balcooa* in Kerala. The study found that the annual litter turnover at the end of May for 2011 and 2012 was 4.064 and 5.087 Mg ha^{-1} $year^{-1}$, respectively. A significant peak in litter fall was observed in February, with a minor peak in December, following a bimodal distribution pattern. Profound seasonal variation was also observed in litter production with rainy season recording the lowest litterfall. The period from November to March accounted for over 70% of total litterfall in *B. balcooa.*

In another investigation by Jijeesh and Seethalakshmi (2016b), they documented that the total litterfall production of *Ochlandra travancorica* between June 2010 and May 2011 was approximately1.846 metric tons per hectare, exhibiting notable variations on a monthly basis. A significant peak in litter deposition was observed in February, while a smaller peak occurred in July. Notably, a significant seasonal fluctuation was observed in litter accumulation, with the wet season showing the least litter accumulation. July marked a minor peak in litter accumulation. During the period from November to March, over 70% of *O. travancorica* litterfall occurred. The study noted that litter production increased monthly during the dry season, while it decreased during the rainy season. Among the components of litter, leaves constituted the majority at 95.34 ± 0.729%, followed by branches (2.90 ± 0.33%) and culm sheaths (1.76 ± 0.41%).

Tripathi and Singh (1995) conducted a study on litterfall production in both mature and recently harvested bamboo savanna habitats within a dry tropical region of India. The findings indicated that in mature and harvested sites, the annual litterfall was 590 g m^{-2} and 267 g m^{-2}, respectively. Leaf litter constituted a weight ranging from 58% to 77% of the total litterfall. Although litterfall was observed year-round, a significant portion (72-83%) of leaf litterfall occurred during the winter months (December to February). The distribution of total litterfall across seasons was as follows: summer (13-22%), rainy season (12-22%), and winter (64-65%) of the year.

Shanmughavel *et al*. (2000) recorded the litter production and nutrient cycling behaviour of *Bambusa bamboo* plantations of different ages. In plantations aged 4, 5, and 6 years, the annual litter production was found to be 15.4 t ha^{-1}, 17 t ha^{-1}, and 20.3 t ha^{-1}, respectively. These values exceeded those of comparable-aged plantations. Litterfall exhibited a bimodal pattern, with all age groups experiencing primary peaks during winter and late summer. Leaf litter constituted 58% of the total annual litter production, while twig litter made up the remaining 42%.

Thomas *et al*. (2014) undertook a study on *Ochlandra setigera,* a rare indigenous bamboo species of the Nilgiri region. The study revealed a total annual litter production was 1.981 t ha^{-1}. Litterfall exhibited a triphasic pattern, featuring two primary peaks in November 2011 and January 2012, along with a smaller peak in July 2011.Jamaludheen and Kumar (1999) also carried out a study on litter production of nine fast growing species in Kerala. They found that the annual litter production ranged from 3.43 Mg ha^{-1} (*Pterocarpus*) to 12.69 Mg ha^{-1} (*Acacia*), with 61% to 96% of the litter being foliage. *Acacia*, *Ailanthus*, *Pterocarpus*, and *Casuarina* exhibited a unimodal distribution in their litterfall pattern.

2.6.2. Litter decomposition:

Litter decomposition is the initial stage of soil organic matter development and a key flux of CO_2 exchange from the soil to the atmosphere(Li-Hua *et al.,* 2014). Litter decomposition involves two concurrent processes: (a) the associated mineralization and humification of substances like lignin and cellulose, carried out by microorganisms, and (b) the gradual release of soluble compounds into the soil, where their carbon and nitrogen components undergo stepwise mineralization (Anderson,1988). The decomposition of plant litter drives essential ecosystem processes such as carbon and nutrient cycling (Giweta, 2020). The decomposition of organic litter supplies approximately 70 to 90% of the nutrients required annually for the growth of forests (Vogt *et al.,* 1986). The rate of litter decomposition varies significantly across various ecosystems, while the slow decomposition rates lead to the accumulation of organic matter and nutrient reserves within the soil, rapid decomposition rates aid in fulfilling the nutrient requirements of plants (Isaac and

Nair, 2005). The litter decomposition also serves as the foundation for numerous food chains within tropical forests. It constitutes a primary energy source for the saprophytes found in the forest floor and soil, where the detritus-based trophic chain holds a predominant role(Ge *et al.*, 2013).

Mineralization of nutrients from decomposing plant residues involves three consecutive phases.

1) **Initial phase:** characterized by leaching and predominant nutrient release.
2) **Net immobilisation phase:** when microbes import nutrients into the litter residue.
3) **Net release phase:** involve decrease in nutrients within the litter.

It's important to note that these phases may not be applicable to all nutrients and types of litter(O'Connell and Sankaran, 1997).

The patterns of nutrient release from decomposing litter do not consistently resemble with those which are observed for mass or carbon (C) losses. While certain nutrients like magnesium (Mg^{2+}), calcium (Ca^{2+}), potassium (K^{+}), and sodium (Na^{+}) are liberated from the litter rapidly or sometimes even more rapidly than, carbon (C), but usually nitrogen (N) and phosphorus (P) are held back within the litter during the initial phases of decomposition. This phenomenon of net immobilization could result in a rise in the nutrient content of the tissue, indicating a net influx of nitrogen (N) or phosphorus (P) into the litter (Prescott,2005). The observed rise in nitrogen (N) and phosphorus (P) levels within decomposing litter are attributed to various factors, including non-symbiotic nitrogen fixation, absorption from the surrounding environment through fungal hyphae that extend into the litter, as well as the contribution of atmospheric precipitation and the deposition of insect excrement and plant material from the canopy (O'Connell and Sankaran, 1997). Potassium exhibits the highest mobility among nutrients and experiences significant leaching during the initial phase, without undergoing immobilization (Lousier and Parkinson,1978). According to Swift *et al.* (1979), the rate of nutrient turnover generally follows a particular sequence: potassium (K) > calcium (Ca) > magnesium (Mg) > phosphorus (P) > nitrogen (N).

Madathil and Kodikunnath (2018) conducted a study to understand the litter decomposition rate and nutrient release pattern of *Thyrsostachys oliveri* gamble in humid tropics of Kerala. They observed that weight of litter decreased exponentially with time. The decomposition rate constant for *T. oliveri* was measured 0.009 day^{-1}, corresponding to a half-life of 77 days. Additionally, the order of nutrient release from the decaying litter was as follows: Mg>N> Ca> P> K.

Jijeesh and Seethalakshmi (2016a) conducted a study focused on understanding the litter decomposition and nutrient release dynamics of *Bambusa balcooa* within a homestead block plantation in Palakkad. It was observed that the mass loss during litter decomposition, characterized by an initial rapid decline followed by a slower rate as the process advanced. The decomposition rate constant for *B. balcooa* was determined to be 0.0115 day^{-1}, corresponding to a half-life of 77 days. Notably, during the decomposition process, over 44% of N was released within the initial 30 days, half of P release took place within 60 days, and more than 40% of potassium K was liberated in the first month. The sequence of nutrient release from the decomposing litter followed the order: Mg > N > Ca > P > K.

Jijeesh and Seethalakshmi (2016b) conducted a study to understand the litter decomposition and nutrient release patterns of *Ochlandra travancorica*, a reed bamboo endemic to the Western Ghats (six years old). They found that decomposition rate constant of *O. travancorica* was 0.014 day^{-1} and the half-life was 49.5 days. Biphasic pattern of litter decomposition was observed (first rapid phase followed by slower phase). The soil's nutrient enrichment resulting from the decomposition of litter (t ha^{-1}) followed the sequence: potassium (K) (0.03) > nitrogen (N) (0.02) = phosphorus (P) (0.02) > calcium (Ca) (0.01) > magnesium (Mg) (0.002). The nutrient release from the decomposing litter mass was in the order Mg > N > Ca > P > K.

Thomas *et al.* (2014) investigated the litter decomposition dynamics and nutrient release of a rare indigenous bamboo species, *Ochlandra setigera*, found in the Nilgiri. They found that the rate of decomposition was influenced by both litter quality and environmental factors, such as the highest temperature, monthly rainfall, and relative humidity. The rainy season exhibited higher mass loss rates during litter decomposition. The determined decomposition rate constant was 0.008 day^{-1}, resulting in t_{50} and t_{99} values of 89 and 641 days, respectively. Furthermore, the annual nutrient inputs into the soil through litter deposition (measured in kg ha^{-1}) followed this sequence: N (33.182) > K (11.609) > Ca (7.488) > P (4.338) > Mg (1.941). As the litter mass underwent decomposition, nutrients were released in the subsequent order: N = Mg > K = Ca > P.

Jamaludheen and Kumar (1999) conducted a study to examine litter decomposition rate of nine fast growing tree species in Kerala. The result revealed that the residual mass of litter experienced an exponential reduction as time progressed, specifically observed in *Ailanthus*, *Pterocarpus*, *Casuarina*, and *Leucaena*. *Paraserianthes* demonstrated a linear trend, while *Emblica* and the two *Artocarpus* species showcased a bi-phasic pattern of mass loss. In terms of influencing factors, both the initial lignin content and the ratio of lignin-N exhibited a negative impact on decay rate coefficients. Conversely, the initial N content demonstrated a positive influence. The release pattern of N followed a triphasic trend, while P and K exhibited a biphasic release pattern.

Kunhamu *et al*. (2009) conducted a study aimed at investigating the influence of thinning on the decomposition of litter and the subsequent release of nutrients in *Acacia mangium* stands located in Kerala. The study revealed that the mass remaining in litter exhibited an exponential decline over time, with the overall mass loss rates displaying a biphasic trend. A significant portion, approximately 60%, of the initial mass loss occurred within the initial 5 months, followed by an additional 90% mass loss by the eighth month. The thinning treatments had a noticeable impact on litter decay, particularly during the initial phase. High thinning intensities led to accelerated rates of decay. Also, the study demonstrated that the thinning treatments did not induce significant alterations in the biochemical composition of the litter, including factors such as initial lignin content, nitrogen (N) content, and the lignin-N ratio.

Isaac and Nair (2005) conducted an experiment to study the litter decomposition in three different tree species. They found that the rate of decay varied among these species. The reduction in weight followed a consistent linear pattern, and its correlation with soil moisture was stronger compared to temperature. The calculated half-life values were 3.2, 3.4, and 4.0 months for *Anacardium*, *Artocarpus*, and *Mangifera* respectively. Nitrogen (N) and phosphorus (P) displayed a two-phase release pattern, while potassium (K) exhibited a continuous release pattern. The months with higher rainfall experienced the greatest weight loss, reaching about 36% for *Mangifera* and *Artocarpus*, and 55% for *Anacardium*. The researchers also concluded that earthworms, fungi, and bacteria were the primary agents responsible for breaking down the intact litter. Towards the later stages, Actinomycetes became more active. Among the three species, Mangifera exhibited the slowest decomposition rate, following this sequence: *Mangifera* > *Artocarpus* > *Anacardium.*

Nath and Das (2011) investigated the decomposition dynamics of three priority bamboo species of homegardens in Barak Valley, Northeast India. The result of the study revealed that leaf litter has higher concentrations of N, P, and K than sheath litter, whereas sheath litter had higher ash-free mass and cellulose content. *B. vulgaris* showed the fastest release of all nutrients compared with *B. balcooa* and *B. cacharensis*, and the relative mobility of nutrients was discovered to be K > P > N. Kumar *et al.*, 2022 conducted a field experiment to investigate the litter decomposition rate of the three Bamboo Species of Sub Himalayan Region of Eastern India. It was observed that decomposition was slow earlier and then increased gradually, within 9 months, the entire litter mass got decomposed due to humid tropical condition of the study area and the primary nutrients decreased gradually as the decomposition progressed.

Bamboo leaf litter, as indicated by O'Connor *et al*. (2000), undergoes an extended and considerably slower process of degradation and decomposition. As noted by O'Connor *et al*. (2000), the majority of bamboo leaf litter resists breakdown by microbial activity. This resilience could be attributed to their high

C:N ratio and complex structural composition, both of which pose challenges for natural decomposition processes. Singh and Singh (1999) report that approximately 28 months are required for 95% of bamboo leaves to undergo decomposition. In contrast, Christanty *et al.* (1996) propose a slightly longer duration of 36 months for complete decomposition of bamboo leaves. These varying estimates underscore the notably prolonged and intricate nature of bamboo leaf litter decomposition.

2.6.2.1. Factors affecting litter decomposition:

Litter decomposition is governed by three primary elements: climate, litter quality, and the characteristics and population of decomposers. In regions characterized by unfavourable weather conditions, climate exerts the most significant influence. However, in more favourable environments, the composition and quality of the litter material become the predominant determinant (Couˆteaux *et al.*, 1995). The roles of these factors in the decomposition process are elaborated in detail under the advancing subheadings.

a) Climatic factors:

Moisture and temperature are reported to be the two most important abiotic factors con trolling the rate of biomass decomposition under natural condition. According to Tripathi *et al.* (2009), the pace of litter decomposition varies with season, being slower in winter and more rapid during the rainy season. The primary factors attributing to the faster rate of litter decomposition during the rainy season are likely the abundance of rainfall, optimal moisture conditions, and an increased abundance of micro-fungi. Kumar *et al.* (2010) similarly arrived at the conclusion that there exists a higher rate of litter decomposition during rainy seasons, accompanied by an increase in weight loss. This phenomenon is attributed to the increase in precipitation, elevated soil moisture content, and increased microbial presence. Temperature also acts as pivotal factor in influencing the rate of decomposition. The pronounced impact of temperature on decomposition predominantly arises from its influence on soil biological activity, as soil microbial activity experiences an exponential increase with rising soil temperature (Krishna and Mohan, 2017). Litter decomposition occurs at a faster pace at lower elevations in contrast to higher altitudes, mainly due to the decrease in temperature as elevation rises, as highlighted by Veen *et al.* (2015).

The rate of decomposition is additionally impacted by soil's physical and chemical attributes. Among these, texture assumes a paramount role as it affects aspects such as water infiltration and porosity (Coleman *et al.*, 1999). According to Cuevas and Medina (1986), soil organic matter exerts an indirect influence on decomposition since the microbial population within the soil relies heavily on organic matter, playing a vital part in both litter blending and decomposition. Furthermore, Devi and Yadav (2007) assert that among soil nutrients, soil nitrogen stands as a pivotal determinant in regulating the pace of decomposition. Dent *et al.* (2006) conducted research indicating that in the context of various litter substrate qualities and decomposition rates across three distinct soil fertility levels in the Malaysian tropical rainforest, the fastest mass loss and nutrient release were observed in alluvial forest litter (associated with nutrient-rich soil), while the slowest decomposition occurred in heath forest litter (linked to nutrient-poor soil).

b) Litter quality:

The composition of chemicals within the decomposing substance, commonly referred to as litter quality, is a key aspect that governs the pace at which decomposition rates take place (Meentemeyer, 1978). Plant litter consists of diverse categories of organic compounds. Among these, there are four main groups of soluble organic substances found in litter, namely sugars, phenolics, hydrocarbons, and glycerides. The soluble sugars, particularly mono and oligosaccharides, pose challenges for metabolic processes. The proportions of these compounds vary depending on the specific plant species and the part of the plant. The assessment of plant litter quality involves analysing the chemical composition of elements like nitrogen, phosphorus, and potassium, as well as significant cell wall constituents such as lignin, cellulose, and hemicelluloses. These factors collectively impact litter decomposition and the subsequent release of nutrients (Swift *et al.*, 1979).

Decomposition rates of litter exhibit considerable divergence even among species undergoing decomposition within the same ecological conditions (Cornelissen, 1996). These variations in decomposition primarily stem from distinctions in litter characteristics, including attributes like leaf durability, nitrogen content, lignin concentration, polyphenol levels, the C/N ratio, and lignin/nitrogen ratio (Perez-Harguindeguy *et al.*, 2000). Of these diverse traits, the nitrogen and lignin composition within plant matter hold the greatest importance in governing the pace of decomposition (Gartner and Cardon, 2004). Litter that possesses a substantial quantity of lignin undergoes decomposition at a slower rate compared to litter with a significant abundance of starch (Berg and Laskowski, 2006). Litter characterized by a high cellulose and lignin content presents a challenge in terms of decomposition, requiring specific microorganisms for breakdown. The pace of litter decomposition is inversely linked with the C/N and lignin/N ratios found in the initial litter. Conversely, it exhibits a positive correlation with the nitrogen content of the initial litter (Berg and Laskowski, 2006). Litters featuring lower C/N ratios experience faster decomposition rates compared to those with higher C/N ratios (Swift *et al.*, 1979). In essence, due to the proliferation of soil microbes, litters rich in nitrogen content experience quicker decomposition than those with lower nitrogen concentrations.

Gosz *et al*. (1973) reported that the process of decay in coniferous tree leaves occurs at a comparatively slower rate than that in deciduous tree leaves. This variation can be attributed to the fact that broad-leaved litter contains higher amounts of potassium and phosphorus, along with lower levels of lignin and consistently fewer ether-soluble components. Kucera (1959) also noted a gradual connection between the pace of decomposition and the ash content of substances soluble in hot water, the rate of decomposition is high in species having high ash content.

In a study conducted by Semwal *et al.* (2003) on leaf litter decomposition and nutrient release patterns of six multipurpose tree species in the central Himalayas, it was observed that the annual rate of decomposition displayed a positive correlation with concentrations of carbon (C) and nitrogen (N), while showing a negative correlation with ratios such as C/N, lignin/N, polyphenol/N, and the combined lignin+polyphenol/N ratios in the fresh litter. Singh *et al.* (1999) conducted a study on the litter decomposition patterns of four native species grown on coal mine spoil in Singrauli. Their findings revealed that lignin emerged as the most reliable indicator for predicting both the annual rates of nitrogen (N) and phosphorus (P) mineralization, as well as the annual rate of mass loss, explaining 90% of the variability. Additionally, there was a positive correlation observed between mass loss and the rates of N and P mineralization.

c) Soil Microbes and fauna:

According to Coleman and Crossley's (1996), soil fauna plays a crucial role in conditioning litter and promoting microbial activity. On the other hand, soil microbes primarily drive the decomposition processes. The key participants in litter decomposition are algae, actinomycetes, bacteria, and fungi, as noted by Schaefer and Schauermann (1990). The abundance and distribution of soil fauna and microbial communities impact the pace of litter breakdown at different decomposition stages (Dilly *et al.*,2004).

Microbial breakdown of organic matter in forest soil significantly influences the flow of soil carbon and energy within the ecosystem (Hättenschwiler *et al.,* 2005). The speed of litter decomposition, nutrient release, and soil fertility are directly linked to the functional roles and metabolic actions of decomposer communities (Swift *et al.,* 1979). Additionally, the processes of litter decomposition, including physical breakdown, organic matter transformation into nutrients, and carbon dioxide release into the atmosphere, are profoundly influenced by the composition of decomposer communities (Dilly *et al.*, 2004). Among these communities, fungi and bacteria are the primary drivers of litter decomposition (Swift *et al.*,1979), but during the later stages of decomposition, actinomycetes become more active Isaac and Nair (2005).

The rate and effectiveness of leaf litter decomposition are influenced by the quantity and activity of decomposers as well as the quality of the substrates involved (García-Palacios *et al.,* 2013). Apart from fungi and bacteria, the soil biota includes both micro- and macroinvertebrates (Heath *et al.,*1966). Among these, microarthropods, which inhabit litter layers and the upper soil strata, play a crucial ecological role by significantly contributing to the decomposition and mineralization of organic matter, nutrient cycling (Irmler, 1982), and soil formation processes. The activities of soil fauna contribute to the conditioning of litter and stimulation of microbial processes.

Observations by Edwards and Heath (1963) indicated that earthworms could decompose litter at a rate three times faster than smaller invertebrates like springtails, enchytraeids, and larvae. In a study by Seeber *et al.* (2006), it was found that primary decomposers *like L. rubellus and C. fulviceps* had a substantial positive impact on decomposition, while the presence of secondary decomposers, either alone or in conjunction with primary decomposers, showed either limited or negative effects on litter breakdown. This led to the conclusion that factors other than the litter quality plays a significant role in the decomposition process.

2.7. Effect of bamboo vegetation on soil health:

Vegetation's significant impact on soil properties is widely known, with individual plant species holding a crucial role in shaping soil fertility within natural ecosystems. Plant species create positive feedback to nutrient cycling through direct processes involving nutrient absorption, utilization, and release, as well as through indirect mechanisms such as litterfall, influencing microbial activity and herbivore interactions (Hobbie, 1992). The dynamic nature of the relationship between plant species and soil results in varying effects on soil properties by different plant species (Das *et al.,* 2007).

Bamboo is fast-growing in nature and also have a dense foliage, so they are able to maintain the thick layer of litter. This litter layer maintains microclimate in the understory and soil moisture, the most important factors for improving soil health and restoration of degraded lands (Solomon *et al.*, 2020). Bamboos are also having extensive root systems and interconnected rhizomes which are often considered suitable for rapidly enhancing soil properties (Kaushal *et al.,* 2020). Moreover, bamboo diversifies the landscapes, providing food and habitat for numerous species of insects, birds, and animals (INBAR, 2018) and in return these organisms directly and indirectly affect understory microclimate and soil health.

2.7.1. Effect on soil physio-chemical properties:

Singh and Kochhar (2005) conducted a field trial to study the physico-chemical properties of soil under *B. pallida* plantation under varying densities. The results revealed that bamboo plantation had a positive impact on nutrient balance in the soil. Notably, the spacing of the plantation had a significant influence on the physicochemical attributes of the soil. As the planting spacing increased, there was a noticeable decline in soil chemical properties. In general, surface soil parameters such as soil pH, electrical conductivity, organic matter, and the cation levels of Ca, Mg, and Zn increased. However, the availability of P, K, and Fe cations decreased across all planting densities.

Kaushal *et al.* (2020) evaluated the impact of seven bamboo species on soil properties. It was observed that bulk density of the soil remained relatively unchanged among the various bamboo species. However, significant improvements were observed in hydraulic conductivity, water stable aggregates and mean weight diameter of the soil. Regarding soil chemical parameters, there were no significant alterations in soil pH, organic carbon content, or available phosphorus under different bamboo species. Conversely, a significant decrease was noted in the levels of total nitrogen and potassium. Significant variations were also observed in the concentrations of secondary and micronutrients across the different bamboo species. Calcium and magnesium levels were found to be the lowest under *B. nutans*, while the highest calcium content was recorded in *D. stocksii* and the highest magnesium content in *B. vulgaris*. Based on their results, they recommended the use of *B. bambos, B. vulgaris*, and *D. hamiltonii* for the rehabilitation of degraded lands prone to soil erosion. These bamboo species exhibited the ability to enhance soil health, making them suitable choices for such restoration efforts.

Kaushal *et al.* (2019) in another study evaluated the soil properties under six bamboo species planted at 5m×5m spacing. They reported that bulk density, soil organic carbon, available N, P, K, and hydraulic conductivity showed significant improvement under bamboo species compared to the control treatment whereas highest soil organic carbon (1.68%), soil phosphorus (27.5 kg ha^{-1}), soil nitrogen (243 kg ha^{-1}), potassium (247.5 kg ha^{-1}) is found in topsoil of *D. hamiltonii*. Based on the results D. *hamiltonii* and *B. balcooa* were found to be better species for maintaining soil fertility status, whereas *D. hamiltonii* and *B. nutans* could be recommended for enhancing soil moisture through better groundwater recharge.

Upadhyaya *et al.*, 2003 carried out a study to determine the physico-chemical properties of soil under the canopy of two bamboo (*Bambusa balcooa* and *Bambusa pallida*) species in Arunachal Pradesh. They reported that certain soil characteristics remained similar between both bamboo species, including soil texture, bulk density, and the concentrations of NH_4^+ -N and NO_3 - N. However, there were significant differences observed in other soil parameters. Specifically, the soil organic matter (SOM), total nitrogen, and available phosphorus were notably higher in the case of *Bambusa pallida*. Conversely, the soil acidity (pH 5.99) was higher in *Bambusa balcooa* compared to *Bambusa pallida* (6.52). The increase in pH observed under *Bambusa pallida* was attributed to the comparatively lower addition of organic matter to the soil through this bamboo species.

Venkatesh *et al*. (2005) investigated the influence of some important edible bamboo species on the soil properties in Northeastern Himalayas. The study results revealed that all the bamboo species had varying effects on soil properties. Specifically, the highest increase in soil pH was observed in *Dendrocalamus giganteus*, followed by *D. hookerii*. There was a noticeable increase in organic carbon content in soils under all the bamboo species. In terms of available nitrogen (N) content, the highest increase was recorded in *Bambusa multiplex* (126.5 kg/ha), followed by *D. giganteus* (94.0 kg/ha). *D. giganteus* and *D. hookerii* had the maximum build-up of exchangeable copper (Cu) and magnesium (Mg) in the soil. However, there was a reduction in available phosphorus (P) in most of the bamboo species, with the highest reduction observed in *D. hamiltonii* (4.4 kg P/ha), followed *by B. multiplex* (3.9 kg/ha). In contrast, the available potassium (K) content increased significantly, with the highest increase observed in *D. hookerii* (207.2 kg/ha), followed by *B. multiplex*. On average, *D. giganteus, D. hookerii*, and *B. nutans* were identified as the most promising species for restoring soil fertility status in the humid tropics of the Northeastern Himalayan region in India.

Tariyal *et al.* (2013) carried out an experiment to evaluate the influence of four major bamboo species plantation on its soil physico chemical properties. At the end of study, they found that all of the bamboo species had a significant influence on the soil properties. Notably, there were considerable variations in Soil Organic Carbon (SOC) levels among the different bamboo species, with the highest SOC content being observed under *Dendrocalamus strictus* (106.56 t ha^{-1}). In term of primary nutrients highest concentration was recorded under *D. strictus* (N= 305.74 kg ha^{-1}, P= 110.12 kg ha^{-1} and K= 134.79kg ha^{-1}).

Kaushal *et al*. (2021a) again conducted a field trial in the Himalayan foothills to investigate the accumulation of carbon fractions in soil under six different bamboo species (fourteen years old). The study revealed that the various bamboo species had a significant impact on the distribution of soil carbon fractions. *Dendrocalamus hamiltonii* exhibited the highest accumulation of various carbon fractions, including very labile carbon (6.12 mg g^{-1}), less labile carbon (2.55 mg g^{-1}), and non-labile carbon (11.40 mg g^{-1}). Also, *D. hamiltonii* recorded the highest levels of active (8.85 mg g^{-1}), passive carbon (13.95 mg g^{-1}), and carbon management index (CMI) (186.04). Additionally, the presence of bamboo plantations, regardless of the species, contributed to an enhancement in Soil Organic Carbon (SOC) fractions and promoted carbon build-up in the soil when compared to open fallow land.

Impact of bamboo (*D. strictus*) plantation on soil redevelopment in dry tropical region studied by Singh and Singh (1999). It was observed that significant changes occurred in soil properties over time. Specifically, they observed an increase in Soil Organic Carbon (SOC) from 0.34 ± 0.02 in the third year to 0.67 ± 0.01 in the fifth year of plantation. Nitrogen content also exhibited an upward trend, rising from 0.04 in the third year to 0.07 in the fifth year. However, Total P however, did not differ significantly with age of the plantation (0.01+0.00). Additionally, a positive feedback relationship exists between Net primary production and the soil redevelopment process. Joshi *et al.* (1991) conducted a study to evaluate soil parameters under bamboo forests. They reported surface have relatively high proportion of nutrients. The order of nutrient percentage concentration in sub surface soil is as follow C>N>K>P.

Prasath *et al.* (2014) conducted a study in Kottur, Tanjore, investigating soil nutrient levels under *Bambusa vulgaris* plantation with three distinct spacing 5×5 meters, 6×4 meters, and 7×4 meters. They reported that soil organic carbon (SOC) content increased under bamboo compared to its initial levels, with the highest level in 7x4m spacing (0.682%), then other two spacing of 6 × 4m (0.678%) and 5 × 5m (0.67%). Nutrient levels (NPK) were highest in 7×4m (312.91, 33.94, 205.89 kg/ha), followed by 6×4m (314.42, 34.10, 206.01 kg/ha), and 5×5m (314.82, 34.27, 206.50 kg/ha). The study demonstrated an improvement in soil nutrient status under bamboo plantation compared to its initial condition, with the 7×4 meters spacing exhibiting the highest levels of soil nutrients (NPK) and SOC among the three spacing options.

Kittur *et al.* (2017) conducted a field trial to investigate the effect of clump spacing of *Dendrocalamus strictus* on soil physicochemical properties. They observed that soil bulk density consistently increased with increasing soil depth across all planting densities. Additionally, there was a general trend of increasing bulk density from closely spaced bamboo clumps to widely spaced bamboo. In terms of nutrient content, the upper 20 cm of soil under in closely spaced bamboo (4×4 meters) had higher levels of Nitrogen (N), Phosphorus (P), and Potassium (K), with values of 2197 kg/ha, 21 kg/ha, and 203 kg/ha, respectively. These values were significantly higher compared to nutrient content found under wider spacing spacings. However, regardless of clump spacing, the nutrient content in the soil decreased with increasing soil depth. Approximately 50% of the N, P, and K were concentrated within the 0–20 cm soil layer.

Akoto *et al.* (2020) conducted a field trail to evaluate the effect of *Bambusa balcooa* based agroforestry system (5m×5m) on soil properties in the arid semi-deciduous zone of Ghana. Their observations revealed that initially, there was no significant effect of bamboo on soil properties. However, by the third year of the trial, several soil characteristics, including Cation Exchange Capacity (CEC), soil moisture, pH, and, in certain cases, the availability of Phosphorus (P), had improved. These improvements were attributed to the increased deposition of bamboo litter in the third year of the experiment, which resulted in increase of soil organic matter and other nutrients (N, P, and K) due to the decomposition of bamboo leaf litter and fine roots.

Naugraiya (2015) conducted a study focused on evaluating soil nutrient locking in an 11-year-old *Dendrocalamus strictus* plantation, spaced at 3×4 m apart. The study revealed that nutrient locking in the top 0-30 cm soil layer, concerning Carbon, Nitrogen, Phosphorus, and Potassium accumulation, was approximately about 272.28 q ha^{-1}, 321.96 kg ha^{-1}, 8.89 kg ha^{-1}, and 234.95 kg ha^{-1} respectively. These nutrients were primarily retained by different parts of the bamboo plant, with the highest nutrient retention occurring in the bamboo culms (37.67%), followed by the belowground rhizomes (28.70%), branches (25.82%), and leaves (7.81%).

Jijeesh *et al.* (2021) reported about nutrient locking in biomass and soil properties of *Munrochloa ritchiei* and *Ochlandra setigera* natural populations situated in the Nilambur Forest Division of Kerala. They documented that the stored amounts of various nutrients in the standing biomass of *M. ritchiei* were as follows: 196.5±87.8 kg ha^{-1} (N), 1988.1±902.9 kg ha^{-1} (P), 977.6±542.1 kg ha^{-1} (K), 48.1±15. kg ha^{-1} (Ca), and 23.2±8.7 kg ha^{-1} (Mg). The soil's nutrient status within the bamboo stand showed that, up to a depth of 60 cm, the total content of NPK in the soil was 30.3±1.3 t ha^{-1}, 81.03±4.01 t ha^{-1}, and 22.97±1.30 t ha^{-1}, respectively. Additionally, Calcium (Ca) and Magnesium (Mg) in the soil were found to be

2.775±0.634 t ha^{-1} and 1.92±0.34 t ha^{-1}, respectively. Investigations into the nutrient status of both the plant and soil indicated that the total nutrient storage within the plant parts followed this order: Stem > Rhizome > Leaves + Branches > Root. Regarding the nutrient storage in the standing biomass stock, it followed the order: P > K > Ca > N > Mg. In *O. setigera*, the total nutrients locked in the biomass components were 306.5±116.2 kg ha^{-1} for N, 2085.9±698.0 kg ha^{-1} for P, 658.8±228.7 kg ha^{-1} for K, 52.1±16.1 kg ha^{-1} for Ca, and 38.4±6.8 kg ha^{-1} for Mg. The total storage of N, P, K, Ca, and Mg in the soil was measured at 21.671±2.238 t ha^{-1}, 83.308±5.106 t ha^{-1}, 7.902±0.148 t ha^{-1}, 1.598±0.702 t ha^{-1}, and 1.132±0.269 t ha^{-1}, respectively.

Kumari and Bhardwaj (2017) carried out an experiment to assess seven bamboo species growth characteristics and the role of pure bamboo plantation in improving soil quality. They observed a positive correlation between different growth and soil parameters. All mineral nutrients were observed to be maximum at a soil depth of 0-20cm. The growth parameters and highest nutrient contents were recorded under *D. asper* as compared to rest of the species.

2.7.2. Effect on soil biological properties:

Soil microbiological activity has a significant impact on the stability and fertility of ecosystems. It is widely recognized that maintaining good levels of microbiological activity is crucial for preserving soil quality. Enzymatic activities within the soil microbiome play a pivotal role in the cycling of nutrients in the soil. These activities are essential for both the breakdown and conversion of organic matter and the transformation of plant nutrients within the soil ecosystem (Dick and Tabatabai, 1993).

Tariyal *et al.,* 2013 investigated the influence of four bamboo species on soil biological properties in North India. The results revealed that microbial biomass carbon was highest under *D. strictus* for both surface and sub surface soil (0.212% and 0.1% respectively) and during rainy season microbial biomass carbon was highest irrespective of species. The highest soil respiration value was observed under *D. strictus* (1426.45mg CO_2 m^{-2} hr^{-1}).

In a study conducted by Wang *et al.* (2004), they examined the distribution of microbial biomass carbon, nitrogen, and phosphorus within soil profiles across five distinct vegetation systems: barren areas, bamboo, Chinese fir, citrus orchards, and rice fields. It was observed that, the bamboo system exhibited higher levels of microbial carbon B:C level compared to the other systems and except for bamboo it decreased as soil depth increased. Regarding microbial biomass nitrogen, the highest concentrations were found in the upper 20 cm of soil in the bamboo system, while in the other vegetation systems, it was more prominent in the 20-40 cm soil layer. The microbial biomass phosphorus recorded in following order bamboo > Chinese fir > citrus orchard > rice field > barren area. Finally, they concluded that management practices and vegetation strongly influence the soil microbial properties.

Kaushal *et al.* (2020) evaluated the soil biological properties under seven bamboo species of Western Himalayan Foothills, India. They reported that Bacterial, fungal and actinomycetes population showed significant variation under different bamboo species, while bacteria is having highest population under *B. bambos*, fungal population is highest under control followed by *D. hamiltonii* (12.2) and actinomycetes population was highest under in control (10.5) followed by *D. hamiltonii* (8.4). Enzymatic activities also showed a significant variation under different bamboo species. Whereas all the enzyme activities *i.e.*, Dehydrogenase activity, β-glucosidase activity, acid phosphatase, and alkaline phosphatase activities are highest under control plot instead of bamboo.

Shiau *et al.* (2017) conducted a study to evaluate the soil improvement of badland soils under thorny bamboo. The results revealed that bamboo increased microbial C and N, soil acid-hydrolysable C, recalcitrant C, and soluble organic C of badland soils. Soil microbial biomass carbon was 7-10 times higher under bamboo plantation in comparison to the bare land soils. Bamboo plantation also recorded the high values of Soil respiration rates and potentially mineralizable N leading to the improvement of badland soils.

Tu *et al.* (2013) evaluated the effect of bamboo plantation on soil rhizosphere enzyme and microbial activities in coastal ecosystem. They found that soil enzyme activities and soil microbial population counts were higher in various bamboo species than bare land with higher values of enzyme and microbial properties were under *Phyllostachys violascens* and *Dendrocalamus minor* forests. Tu *et al*. (2014) again conducted an assessment study of rhizosphere soil enzymatic and microbial activities within bamboo forests in southeastern China. Their findings revealed that soil enzyme activities were notably higher in bamboo forests compared to control plots. Specifically, catalase activity showed a significant decrease, with the order of decline being *A. edulis* > *D. vario-striata* > *D. oldhami* > *D. beecheyana var. pubescens* > *P. amabilis*. Furthermore, the populations of bacteria, fungi, and actinomycetes were substantially greater in the bamboo plots when compared to the barren land. Among the five bamboo species studied, *D. oldhami* exhibited the highest total amount of microorganisms.

Garg *et al*. (2013) investigated the microbial activities in the rhizospheres of seven exotic bamboos, intending to explore the potential of soil microbes and mycorrhizae along with these exotic bamboos in mitigating the elevated CO_2. The study's results revealed that the arbuscular mycorrhizae and other microbe activities are very important in maintaining the soil carbon to a great extent in association with bamboo roots. The study also concluded that bamboo is a potential candidate for sequestering carbon dioxide.

Zhang *et al.* (2020) carried out a study to determine the soil bacterial community structure of mixed bamboo and broad-leaved forest. They reported that soil bacterial diversity community structure and dominant flora changed under different mixing ratios of bamboo and broad-leaved trees. The bacterial diversity index is more significant in the stand with a mixed ratio of 10–20%, while the diversity was lowest in the 20–30% stands. In the 20–30% forest soil, Acidobacteria were more prevalent than in soils from other mixed-ratio stands.

Materials and Methods

3. MATERIALS AND METHODS

The present study entitled “Litter dynamics and soil changes under six-year-old bamboo stands” was carried out at the College of Forestry, Kerala Agricultural University, Thrissur during October 2022 to September 2023. The details of site characteristics, materials used, and methodology adopted for the study are described in this chapter.

3.1. General description of the Experimental Site:

3.1.1. Location

This study aiming at comparison of litter dynamics and soil changes under selected bamboo species was conducted in an established six year old bambusetum (2016) near to the campus of College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur during 2022 -2023 covering an area of over 1 hectare (10°32’ N latitude and 76°26’ E longitude) with an altitude of 40 m above mean sea level.

3.1.2. Climate

Agroclimatic data for the study area covering the period from September 2022 to September 2023 were obtained from the Agrometeorological Observatory situated at the Kerala Agricultural University, and the information is presented in the Table 1 and Fig. 1. Vellanikkara is characterized by a tropical warm humid climate, with an annual mean rainfall ranging between 2650 to 3200 mm, with most of the rainfall occurring during the southwest monsoon season, which spans from the month of June to September.

3.1.3. Soil

The soil of the experimental site was characterized as deep well-drained sandy clay loam of the Ultisol order, specifically identified as Typic Plinthustult from the Vellanikkara series. It falls under the midland laterite category and experiences Ustic moisture regimes, with a dry period typically occurring from February to May. The temperature regimes in this area are Isohyperthermic.

Table 1: Monthly weather data of the study area (September 2022 – September 2023) at Vellanikkara, Thrissur

Month	Mean Max. Temp. (°C)	Mean Min. Temp. (°C)	Rainfall(mm)	Rainy days
September	31.1	23.7	167.5	12
October	32.0	23.6	69.6	9
November	32.4	23.0	75.4	7
December	32.2	22.6	91.7	3
January	32.7	21.9	0.0	0
February	35.4	21.9	0.0	0
March	36.1	24.2	1.7	0
April	36.8	25.5	108.3	2
May	34.7	25.7	23.4	4
June	31.8	24.4	276.3	16
July	29.6	23.7	667.3	21
August	32.5	24.4	25.3	3
September	30.7	23.7	516.7	25

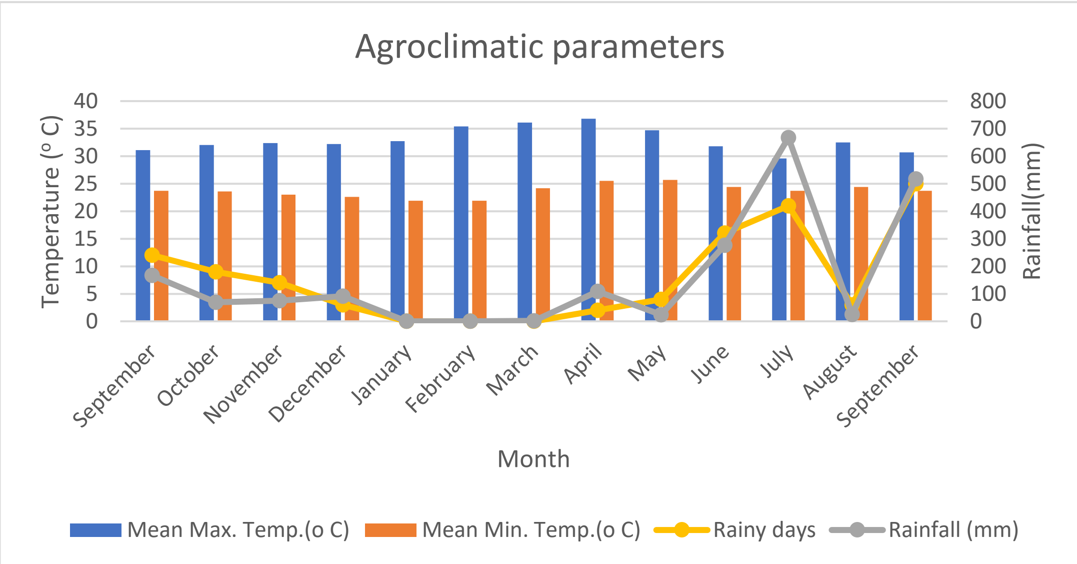


Fig. 1. Weather data of study area during September 2022 to September 2023 at Vellanikkara, Thrissur

3.2. Field lay out:

The experiments were conducted in existing bambusetum near the College of Forestry Vellanikkara, Kerala, India. Six bamboo species viz. *Bambusa vulgaris*

Schrad*, Bambusa balcooa* Roxb.*, Bambusa tulda* Roxb.*, Dendrocalamus brandisii* (Munro) Kurz.*, Dendrocalamus asper* (Schult.f.) Back.ex Heyne *and Dendrocalamus longispathus* Kurz planted at a spacing of 5m×4m in year 2016 covering an area of over 1 hectare. Each plot containing 20 bamboo clumps. These bamboo species were chosen for the study from the priority list of the International Network on Bamboo and Rattan (INBAR,2023) and National Bamboo Mission, India. The study aimed to understand the growth variation, litter dynamics of selected bamboo species, and their influence on soil health status in the humid tropical region of central Kerala.

3.2.1. Brief description of the six selected bamboo species:

1. *Bambusa vulgaris* Schrad.

Bambusa vulgaris is native to Indo-China range but it is also cultivated across a wide range around the world. It grows well upto 870 m elevation with annual rainfall of 1364 – 2585 mm and 25°C temperature. It is usually characterized by its tufted growth pattern, with upright culms and patchymorph rhizomes (Branco *et al.,* 2020). The culms are loosely clustered, with drooping tips, exhibiting a gentle curvature at their base and grow to a height of 8-15 m, having diameter in-between 5 to 9 cm, internodal length 20-30cm and wall thickness of 7.3-15mm. Branching emerges from lower nodes and progresses upwards (Maviton and Sankar, 2023). Leaves are glabrous, 15-25 cm long and 2.5-5 cm wide (Kaushal *et al*., 2021b). Naturally it is a sterile species which don't flower and produces seed, but it can be easily propagated by culm and branch cuttings (Maviton and Sankar, 2023).

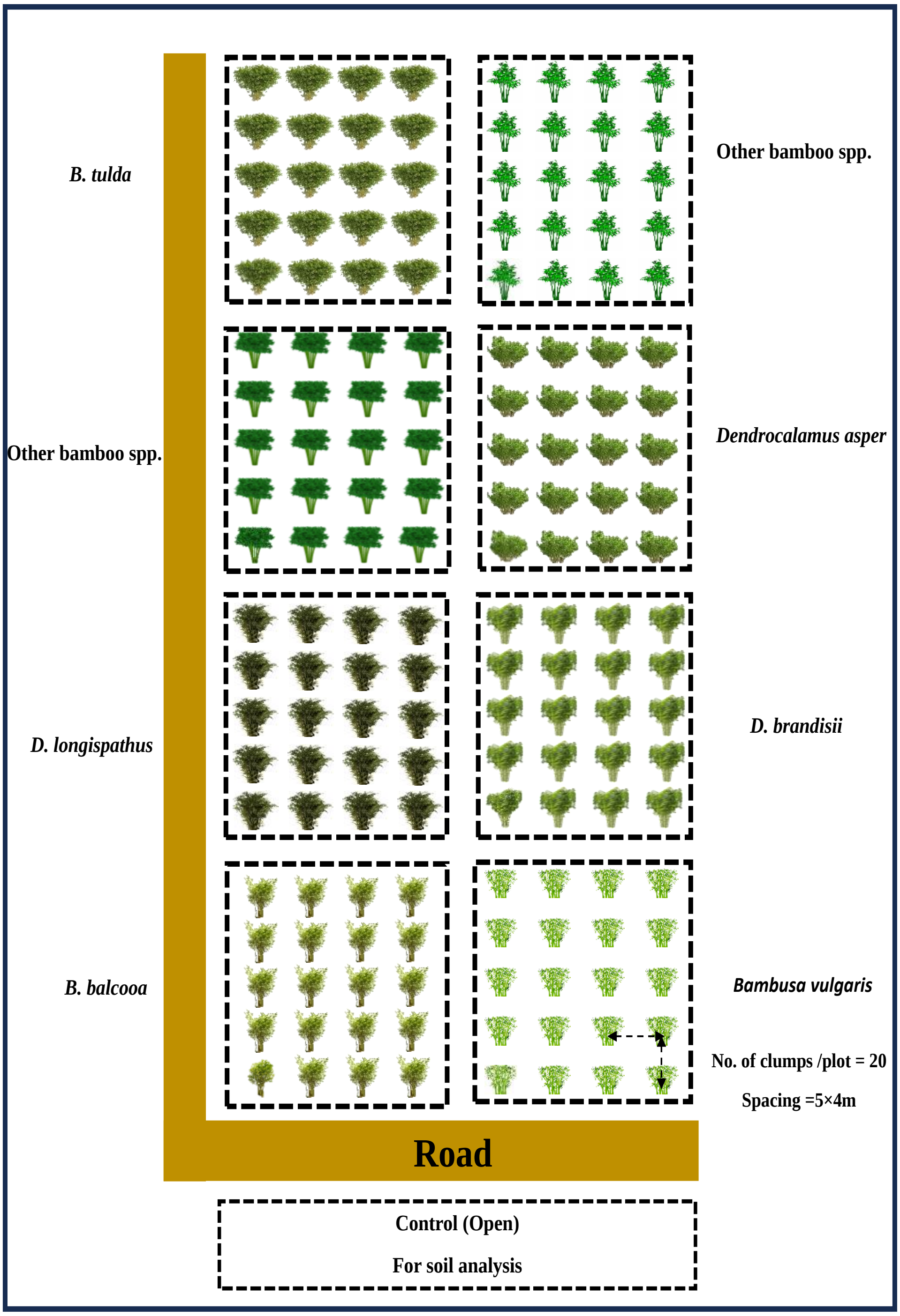


Fig. 2. Schematic representation of the selected six bamboo species in the bambusetum, KAU Vellanikkara, Thrissur.

2. *Bambusa balcooa* Roxb.

Bambusa balcooa is known as Bheema bamboo. It is native to N.E. India and Bangladesh, but it is also successfully introduced in many parts of the world (Benton, 2015). It is commonly known as Baruwa (Assam) and Barak (Tripura). It is an evergreen bamboo characterized by highly tufted growth pattern having small patchymorph rhizome (Viswanath *et al.,* 2021). The culm can attain height of 15 - 31 m with curved top. Mature culms of this bamboo species have diameter range between 8-15 cm and wall thickness between 38.0–41.0 cm(middle). The culm displays robust branching, particularly with thorn-like branchlets that develop at the lower nodes. This species grows best in moderate to high rainfall (2500–5000 mm) area having heavy textured soil with good drainage. It can withstand temperature range of -5 to 20.3 °C (Maviton and Sankar, 2023). Gregarious flowering and seed-setting typically occur at intervals of approximately 35 to 45 years (Seethalakshmi and Kumar, 1998). It is usually propagated by rhizome offsets and two node cuttings (Maviton and Sankar, 2023). *Bambusa balcooa* is commonly used for construction, eating, scaffolding, paper and pulp, woven mats, and farm implements etc (NBM, 2019).

3. *Bambusa tulda* Roxb

Natural distribution of *Bambusa tulda* range between Himalaya to China (Yunnan) and Southeast Asia. It is commonly known as Bengal bamboo, Jati ban (Assam), mritinga (Tripura) and spineless Indian bamboo. It is an evergreen sympodial bamboo with erect culms with drooping tips and flexuous base. Culm usually attain height of 8-30 m, 5–10 cm diameter. Branching in this bamboo species typically begins from the fourth node and extends upward. The leaves are typically linear-oblong or linear-lanceolate in shape, measuring 15-25 cm in length and 2-4 cm in width, with a rounded base (Singh *et al.,* 2010). This plant thrives in the moist, lowland tropics and can be found at elevations of up to 1,500 meters. It grows best in regions where the annual day time temperatures typically range from 22 to 28 °C, but it can also tolerate temperatures between 9 and 32 °C. Additionally, it prefers an average annual rainfall between 1,200 and 2,500 mm. This species exhibits sporadic as well as gregarious flowering patterns (Vanlalfakawma *et al.,* 2021). The estimated duration of its flowering cycle ranges from 15 to 30 years. It can be propagated by rhizome offsets, branch cuttings, culm cuttings and tissue culture. The species found its uses for agarbathi sticks, handicrafts, edible shoots and paper and pulp industries etc.

4. *Dendrocalamus brandisii* (Munro) Kurz.

Dendrocalamus brandisii is commonly known as Burma bamboo and Velvet leaf bamboo. It is naturally found in south – central China and introduced in Indian subcontinent. It mostly grows in wet, evergreen tropical forest at elevations of up to 1300 m. It is large, tall, evergreen bamboo with upright culms. The culms can reach heights upto 19 - 33 m and diameters of 13 - 20 cm, with internodes 30 - 38 cm long (Narasinmhamurty *et al.,* 2013). In this species gregarious flower occur with 40-50 years flowering cycle (Viswanath *et al.,* 2013). It can be propagated through seeds, branch cutting, culm cutting and micropropagation. Young shoots are edible (Rao *et al.,* 1998). It is often used for furniture, construction, handicraft, fencing poles and basket making etc.

5. *Dendrocalamus asper* (Schult.f.) Back.ex Heyne

Dendrocalamus asper commonly known as sweet bamboo, rough bamboo and giant bamboo. It is distributed naturally from Bangladesh to Taiwan to Malaysia to China (Maviton and Sankar, 2023). It is a tall evergreen sympodial bamboo. It reaches a height of 20- 30 m, having a diameter ranging from 8-20 cm, 20 to 45 cm long internodes, and exhibits relatively thick walls (Hossain *et al.,* 2018). It thrives best in humid areas with fertile, heavy soils, from lowlands up to altitudes of 1500 m with an average annual rainfall of 2400mm. It can be propagated by seeds, clonal propagation and tissue culture (Maviton and Sankar, 2023). The delicate, young shoots of this plant are harvested and consumed as a vegetable, often regarded as the most superior among all tropical Asian bamboo varieties (Sowmya *et al.,* 2015). The matured culms are used in paper and pulp industry, handicraft, musical instrument, furniture etc.

6. *Dendrocalamus longispathus* Kurz

It is commonly known as Rupai (Tripura) and Khang (Bengali). It is large clump-forming subtropical bamboos with large branches and leaves and are usually thick-walled. The culms typically reach heights of 10-18 m. When young, they have a bluish-green hue, which turns to a greyish-green colour when matured. The nodes are slightly enlarged and often have roots, internodes 25-60 cm long and 6-10 cm in diameter. They are covered with long, papery remnants of sheaths and have a dark-brown pubescent texture. The culm walls are approximately 1.2cm thick (Sailo *et al.,* 2020). This species is native to several countries, including Bangladesh, Myanmar, India, and Thailand. In India, it naturally occurs in regions such as Assam, Meghalaya, Mizoram, and Tripura (Debnath *et al.,* 2020). It performs well in areas having 20–27 °C temperature and 1800–6000 mm rainfall. *D. longispathus* is recognized for having both sporadic and gregarious patterns of flowering (Naithani, 2015). It is propagated by rhizome offshoots, culm cuttings, branch cuttings and tissue culture. This species holds significant economic importance in the paper industry. Additionally, it finds applications in crafting baskets and containers. Moreover, the tender shoots are occasionally consumed as a food source (Devi *et al.,* 2014).

3.3. Growth performance of selected bamboo species

To understand the growth performance of selected bamboo species, a comprehensive evaluation of their growth and biometric attributes was conducted on six selected bamboo species. From the 20 clumps of each bamboo species within every block, four clumps were chosen at random and taken as replicates for the study. Subsequently, 10 culms were selected from each of these chosen clumps for data collection. To ensure proper identity during observations, the selected culms were appropriately tagged. Various growth parameters, including clump height, clump circumference, culm girth, internodal length, and the number of culms per clump, were observed at regular intervals for four months. The assessment of the growth performance of these selected six bamboo species spanned a duration of 1 year, started from October 2022 and concluding in October 2023. The initial observation was recorded in October 2022, followed by a second assessment four months later in February 2023, third assessment in June 2023, with the final assessment done in October 2023.

Biometric observations of Bamboo

3.3.1. Clump height

Clump height is the straight distance extending from tip of the clump to the ground level. From the selected bamboo clump the total height of the leading bamboo culm was measured from the ground level to the leading terminal tip using Forestry pro (Nikon) instrument and the clump height was expressed in meters (m).

3.3.2. Culm girth

The culm girth was measured at the 5th internode using a measuring tape and expressed in centimetres (cm).

3.3.3. Number of culms per clump

For assessing the number of culms per clump, total enumeration of selected clumps was done. The number was taken by manually counting all the matured culms upto one year old sprouts. The result was recorded as the number of culms per clump.

3.3.4. Clump circumference

The clump circumference was measured using measuring tape at the breast height (1.37 m above the ground level) and expressed in meters (m).

3.3.5. Internodal length

The internodal length was measured at 5th internode of each selected culm using measuring tape and expressed in centimetres (cm).

c

Plate 1: Growth observation of bamboo a) Internodal length, b) culm girth, c) clump circumference

3.4. Litter dynamics

3.4.1. Litter quantification

Specially designed circular litter traps (Hughes *et al.*,1987), were used for litter collection. Each trap was constructed using three galvanized iron wires, each measuring 210 cm in length. Two of these wires were bent into a U shape to create the four legs of the litter trap, while the third was shaped into a 55 cm diameter hoop by securely fastening the wire ends together. This hoop was affixed horizontally onto four legs of litter trap. A plastic gunny bag was inserted into the hoop with its narrow end pointing downwards. Each trap possessed a collection area of 0.24 m^2. The litter traps were positioned 30 cm above the ground surface, secured in place with galvanized wire inserted 5 cm into the soil. Eight such traps per species (total Forty-eight) were randomly placed in interspaces of bamboo clumps on 30th September 2022. Monthly litter was collected from each trap over a one-year period, starting from 1st October 2022 to 30th September 2023. The collected leaf litter was sorted into categories of twigs, leaf, and sheath. Subsequently, the collected litter samples were brought to the laboratory and subjected to oven drying at 70°C until a constant weight was achieved. The average amount of litterfall (species wise), per unit area basis was than calculated for each month.

3.4.2. Litter decomposition

The standard litter bag technique was employed to study the litter decomposition dynamics (Bocock and Gilbert, 1957). Freshly fallen leaves from six selected bamboo species viz. *Bambusa vulgaris, Bambusa tulda, Bambusa balcooa, Dendrocalamus longispathus, Dendrocalamus brandisii,* and *Dendrocalamus asper*, were collected and air-dried for approximately 48 hours in the shade.

a

b

c

d

Plate 2: Litter production observations a) litter trap preparation, b) litter trap installation, c) litter collection, d) sorting of litter into different components.

Plate 3: Litter decomposition observations a) litter bag preparation, b) litter filled litterbag c) placement of litter bags d) retrieval of litterbags, e-g) digestion of litter samples.

Twenty-gram samples of these leaves were then packed in the litter bags of 20 cm × 20 cm size, made of 2 mm nylon wire mesh. Triplicate samples of representative litter from each species were collected to determine the ratio of fresh to dry matter while transferring litter into the bags. These bags were then placed on the surface soil layer with a thin layer of soil covering them. In total, there were 216 litter bags (36 bags per species: 6 species × 12 Months × 3 replication) were employed in the present study. The rows of litter bags were marked with bamboo pegs tagged using plastic tags for easy detection during retrieval of litter bags.

At monthly intervals, three litterbags were retrieved for each species starting from October,2022 up to September 2023. This was done by carefully removing accumulated soil, and litter over the bags and then bringing the bags to the laboratory. In lab, all extraneous materials such as insects, fine roots, and soil were carefully removed and then litterbags were washed under running water, the litter remaining in the bags were then transferred into paper bags and then oven-dried at 70° C for 48 hours and weighted. Mass loss of litter from initial weight (20g) was recorded as litter decomposed.

3.4.2.1. Chemical analysis of litter samples

After oven drying the litter samples were powdered using Wiley mill. The powdered samples were then stored in properly labelled airtight containers or plastic zip lock bags for further chemical analysis.

3.4.2.1.1. Digestion of litter samples

For nitrogen estimation, powdered samples (1g) were first taken into digestion tube and 10 ml of conc. H_2SO_4, 1g digestion mixture (K_2SO_4:$CuSO_4$, 10:1) and pinch (0.1g) of selenium powder were added. This mixture was kept for pre-digestion overnight at room temperature and then digested using block digester (Rotek) in digestion chamber at a temperature of 360°C till the sample became clear. After the digestion, tubes were taken from chamber and allowed to cool. Each digested sample was transferred to 100ml standard flask and made upto the mark.

In case of phosphorus and potassium estimation, 1g plant samples was digested using 10 ml di- acid mixture (HNO_3 + $HCLO_4$) until clear solution was obtained.

3.4.2.1.2. Nitrogen

The triplicate digested samples belonging to each month of sampling were analysed by using Kjelplus classic DXVA for the estimation of the nitrogen.

3.4.2.1.3. Phosphorus

Phosphorus in digested plant samples was analysed using vanado-molybdo-phosphoric yellow colour method with the help of spectrophotometer at 420 nm wavelength (Jackson, 1958).

3.4.2.1.4. Potassium

Potassium in digested plant samples was analysed using flame photometry method (Jackson, 1958).

3.4.2.2. Mass remaining in the litter

The monthly mass loss from the decomposing litter was calculated using the following equation (Olson, 1963).

$$\% \text{ Mass loss} = \frac{(\text{Initial mass} - \text{Final mass})}{\text{Initial mass}} \times 100$$

3.4.2.2.1. Nutrients remaining in the litter

The nutrient content of decomposing litter was calculated using the following equation.

$$\% \text{ nutrient remaining} = \left(\frac{C}{C_o}\right) \times \left(\frac{D_M}{D_{Mo}}\right) \times 100$$

Where, C represents the concentration of the element in the litter at the time of sampling, while C_o stands for the concentration of the element in the initial litter used for decomposition. D_M is the mass of dry matter at the time of sampling, and D_{Mo} represents the mass of the initial dry matter placed for decomposition (Bockheim *et al.*, 1991).

3.4.2.3. Rate of litter decomposition

The rate of decomposition was compared using decay rate(k), which were determined using the widely employed first-order negative exponential decay model (Olson, 1963).

$$\frac{X_t}{X_o} = e^{-kt}$$

Where, X_0 and X_t are initial and final litter masses, k is decay rate, e is base of natural logarithm and t is the time.

The half-life period ($t_{0.5}$) is the time required for the 50%, decomposition of the initial litter, were calculated based on the k-values using the following equation (Olson, 1963).

$$t_{0.5} = \ln (0.5) / - k$$

$$t_{0.5} = - 0.693/ - k$$

3.5. Soil Analysis

3.5.1. Collection and processing of the soil samples

Soil samples were collected from five distinct depths (0-20 cm, 21-40 cm, 41-60 cm, 61-80 cm, and 81-100 cm). Three representative samples were collected from each of the selected bamboo species under study, as well as from the open plot, at these five different depths. However, for the analysis of soil biological parameters, only surface layer (0-20 cm) were considered due to the higher significance of the surface soil layer. Upon collection, the soil samples were air-dried in the shade and then finely processed by grinding to convert them into a powdery form. Subsequently, the powdered samples were sieved through a 2mm sieve to remove any tiny extraneous materials. The samples then kept in clean labelled cloth or plastic bags. The prepared samples were then transported to the laboratory for the analysis of various soil physicochemical properties. In the case of biological properties, fresh soil samples were collected prior to analysis. The soil samples for analysing physico-chemical and biological parameters were collected at the start and again at the end of the study.

3.5.2. Soil physical properties

3.5.2.1. Bulk density (g cm $^{-3}$)

For measuring soil bulk density core sampler method was used (Gupta and Dakshinamoorthy, 1980). The core was inserted into undisturbed soil in the field and samples was collected in the core. The core was taken out and its edges were meticulously levelled by trimming them with a sharp knife. The samples were immediately brought to the lab and oven dried at 105°C till constant weight was achieved. Then bulk density was calculated by the formulae:

$$\text{Bulk Density (g cm}^{-3}\text{)} = \frac{\text{Oven dried weight (g)}}{\text{Volume of soil (cm}^3\text{)}}$$

3.5.2.2. Particle density (g cm $^{-3}$)

To determine the particle density, first weigh an empty 100ml volumetric flask. Then, fill the flask with quarter portion of dry soil and record the weight. Add approximately 50ml of distilled water to the flask and gently warm it to release trapped air in the soil. Allow it to cool, and then carefully fill it up to the mark. Discard the contents and refill the flask with distilled water to the mark, recording the weight again. The particle density can be calculated using the formula:

$$\text{Particle density (g cm}^{-3}\text{)} = \frac{\text{Mass of solid particle}}{\text{Volume of soil (without pore space)}}$$

3.5.2.3. Soil porosity (%)

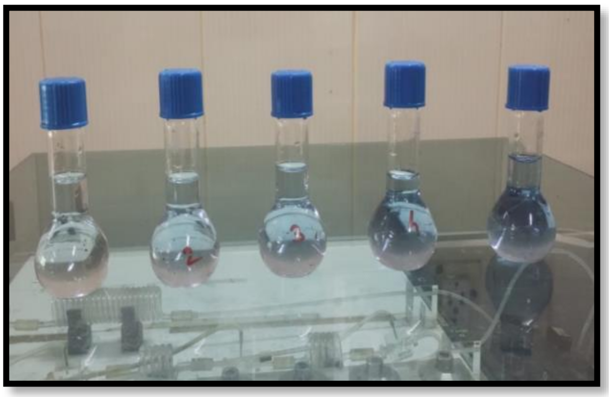
Soil porosity is the measure of percent pore space of the soil. It is the ratio of volume of pore space to the total volume of the soil. Porosity was calculated by using following formula (Black *et al.,* 1965).

a

b

c

d



e

f

g

Plate 4 Soil physico chemical analysis a) soil profile b) bulk density, c) particle density, d) Available Nitrogen, e) Available Phosphorus, f) Available Potassium, g) Soil organic carbon

$$\text{Porosity (\%)} = 1 - \frac{D_b}{D_p} \times 100$$

Where, D_b = Bulk density

D_p = Particle density

3.5.2.4. Soil moisture (%)

Moisture content of soil was measured by gravimetrical method, after collection of samples immediately brought the samples to the lab record the fresh weight of soil then place the samples in hot air oven at 105°C till constant weight was achieved and record the weight. The moisture content was expressed in percentage and calculated by using following formula:

$$\text{Soil moisture (\%)} = \frac{(\text{Fresh weight} - \text{Dry weight})}{\text{Fresh weight}} \times 100$$

3.5.3. Soil chemical properties

3.5.3.1. Soil PH

Soil pH was determined in 1:2.5 soil: distilled water suspensions using digital pH meter (Jackson, 1973).

3.5.3.2. Soil EC (dS m^{-1})

The soil electrical conductivity was measured using the same 1:2.5 soil: distilled water suspensions prepared for pH determination. After recording the pH the suspension was allowed to settle down till clear supernatant was obtained. The soil EC was determined using conductivity meters (Jackson, 1973).

3.5.3.3. Soil organic carbon (%)

Organic carbon content in soil was estimated by wet digestion method (Walkley and Black,1934). The soil samples collected from the five different depths (0-20 cm, 21-40 cm, 41-60 cm, 61-80 cm, and 81-100 cm) were air dried and sieved through 0.2 mm sieve. From this 1g of sample was taken into 500ml conical flask and 10ml $K_2Cr_2O_7$ and 20 ml of H_2SO_4 was added and mixed thoroughly then kept for 30 minutes to undergo oxidation. After 30 minutes 200ml distilled water was added to stop the reaction, 3-4 drops of ferroin indicators were added to mixture and were then titrated with 0.5 N $FeSO_4$ solution. The soil organic carbon was estimated using equation:

$$\text{Soil organic carbon (\%)} = \frac{(\text{Blank value} - \text{Titre value}) \times 10 \times 0.003}{\text{Weight of soil (g)} \times \text{Blank value}} \times 100$$

3.5.3.4. Available Nitrogen (kg ha^{-1})

Alkaline permanganate method (Subbiah and Asija, 1956) was used to determine the soil available nitrogen at five different depths (0-20 cm, 21-40 cm, 41-60 cm, 61-80 cm, and 81-100 cm).

$$\text{Available N (kg ha}^{-1}\text{)} = (V \times 0.00028 \times 2.24 \times 10^6)/5$$

3.5.3.5. Available Phosphorus (kg ha^{-1})

Available phosphorus in soil sample was determined by Bray No. 1 reagent (Bray and Kurtz, 1945). The phosphorus content in soil was determined calorimetrically by reduced molybdate Ascorbic acid blue method (Watanabe and Olsen,1956). Initially, 5g of soil were placed in a 100 mL beaker. Subsequently, 50 mL of Bray No.1 reagent was added, and the mixture was shaked for 5 minutes. The resulting extract was then filtered, and 5 mL of this filtrate was carefully pipetted into a 25 mL standard flask. To this, 4 mL of reagent B was added, and the contents were thoroughly mixed. The intensity of the blue colour produced was measured using a spectrophotometer at a wavelength of 660 nm after appropriate standardization.

$$\text{Available P (ppm)} = R \times \frac{50}{5} \times \frac{25}{5}$$

Where, R = spectrophotometer reading

$$\text{Available P (Kg ha}^{-1}\text{)} = \text{ppm} \times 2.24$$

3.5.3.6. Available Potassium (kg ha^{-1})

The available potassium in soil at different depths (0-20 cm, 21-40 cm, 41-60 cm, 61-80 cm, and 81-100 cm) was determined by taking 5 g of soil and adding 25 ml of neutral normal ammonium acetate solution. The soil solution was subjected to shaking for 5 minutes and then filtered immediately through Whatman No. 42 filter paper, this extracted soil solution is then subjected to flame photometer and reading were recorded after standardization (Jackson, 1958).

$$\text{Available potassium (kg ha}^{-1}\text{)} = \frac{\text{R×Volume of extract (ml)}}{\text{Weight of soil (5g)}} \times 2.24$$

Where, R = flame photometer reading

3.5.3.7. Available calcium and magnesium (mg kg^{-1})

The soil solution extracted from the neutral normal ammonium acetate solution was used to estimate the available Ca and Mg using Atomic absorption spectrophotometer.

Available Ca and Mg (mg/Kg soil) = µg Ca/Mg/ml of the aliquot × 5

3.5.3.8. Available Sulphur (mg kg^{-1})

Soil sulphur was extracted using 0.15 % $CaCl_2$ solution as per the method given by William and Steinbergs (1959) and the sulphur content was determined by turbidimetric method given by Chesnin and Yein (1951).

$$\text{Available sulphur (mg/Kg soil)} = \frac{\text{Sample Absorbance}}{\text{slope of std.curve}} \times 12.5$$

3.5.4. Soil biological properties

3.5.4.1. Total microbial count

Total microbial count was done by "Serial dilution plate technique (Johnson and Curl, 1971). Specific type of growing media were used for particular groups of microbes for example soil extract agar medium for bacteria, Martin's Rose Bengal agar medium for fungi and Ken Knight's Agar medium for actinomycetes.

First, weigh 10g soil sample and mix it in 90 ml sterile blank. Mix thoroughly and shake for 15 min for complete dilution (10^{-1} dilution). From this transfer 1 ml of the suspension to 9ml water blank (10^{-2} dilution), repeat it till 10^{-6} dilutions are obtained. Transfer one ml of appropriate dilutions to sterile Petri dishes (Mostly 10^{-5} or 10^{-6}can be used for bacteria 10^{-3} or 10^{-4} for fungi and 10^{-4} or 10^{-5} for actinomycetes). For each dilution maintain 2-3 replications. Pour 20 ml of cooled media (just before solidification) in Petri plates and mix by moving clockwise and anti-clockwise direction for 3 to 4 times and allow it for solidification. Incubate the plate in an inverted position at 28°C room temperature for 2 - 14 days. Observe the bacterial colonies after 2 days; fungi for 5 to7 days; actinomycetes after 7- 14 days. The total microbial count was recorded by counting the colonies per plate, calculating the population and expressed as colony forming units per gram of soil (cfu/g) (Martin, 1950).

$$\text{No. of microorganism/ g of soil} = \frac{\text{Number of colonies}}{\text{Amount plated} \times \text{Dilution factor}}$$

3.5.4.2. Dehydrogenase activity

The dehydrogenase activity was estimated as per the procedure described by Casida *et al.,* (1964), About 1 g of air-dried soil was weighed and taken in an airtight screw capped test tube, to which 0.2 ml of 3 % triphenyl tetrazolium chloride solution was added in each tube. Gently tap the bottom of the tube to remove all trapped oxygen, and thus a water seal was formed above the soil and ensured that no air bubbles were formed in tube. Tube was incubated at 28 $\pm$0.5°C for 24h. After incubation 10 ml methanol was added and the contents were vigorously shaken for proper mixing. Samples were allowed to stand for 6 h. The clear, pink coloured supernatant was obtained, and the readings were taken with a spectrophotometer at a wavelength of 485nm. A series of standards were used for preparing the calibration curve. The results were expressed as dehydrogenase activity and expressed in terms of Triphenyl formazan hydrolysed per gram of soil per 24 h in micrograms.

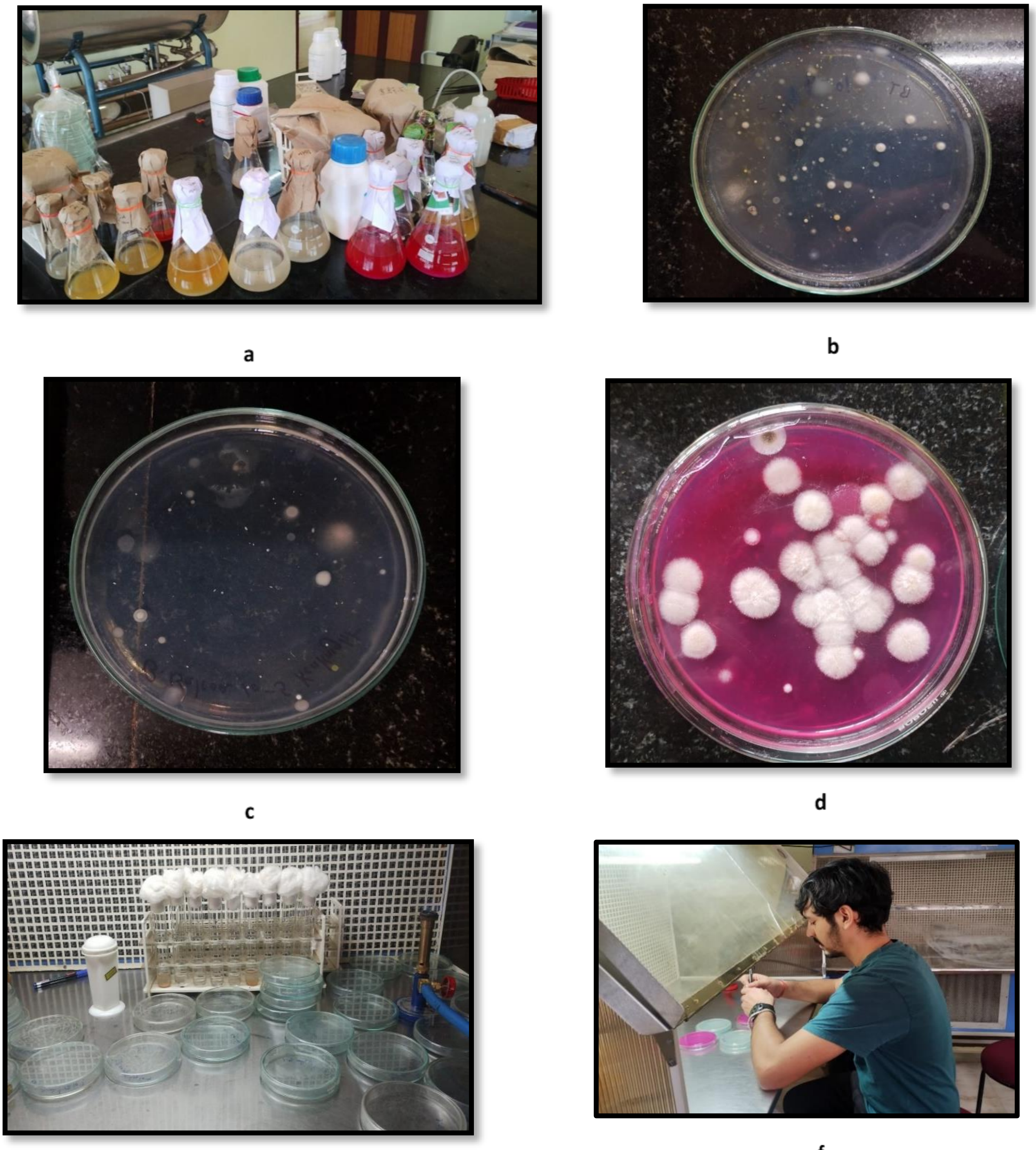


Plate 5 Soil microbial analysis a) preparation of media, b) bacterial colonies, c) actinomycetes colonies, d) fungal colonies, e) laminar airflow, f) counting microbial colonies

3.6. Statistical analysis

Collected data were analysed using R-studio and Microsoft Excel 365 version. Bamboo growth parameters, litterfall and litter decomposition were analysed using univariate ANOVA and treatment means were compared using least significant difference ($P<0.05$) wherever appropriate. Univariate ANOVA was performed to assess the variations in nutrient concentration and the percentage of remaining nutrients in monthly-collected litter samples, considering both species and months. Analysis of soil parameters were also done by using univariate ANOVA in each depth of across selected bamboo species. The analysis facilitated the examination of parameter variations within the selected bamboo species at different depths.

Results

4. RESULTS

The results of the present investigation entitled “Litter dynamics and soil changes under six-year-old bamboo stands” have been presented in detail in this chapter. The results of different aspects on growth performance, litter dynamics and soil physico chemical and biological properties in six different bamboo species studied are presented under different subtitles as below.

4.1. Growth performance of selected bamboo species

The growth performance of six selected bamboo species, including measurements of culm girth, internodal diameter, number of culms per clump, clump circumference, and clump height, has been documented here under. These growth observations were collected at intervals of four months over the course of the study.

4.1.1. Clump height (m)

The variation in clump height of different bamboo species is presented in Table 2. The clump height shown a significant difference among different bamboo species. During first observation maximum clump height was observed in *Dendrocalamus brandisii* (13.77m) which was statistically at par with *Dendrocalamus longispathus* (12.90m) *and Dendrocalamus asper* (12.05m). Conversely, the minimum and significantly lowest clump height was observed in *Bambusa tulda* (9.25m). Again, during second, third and fourth observation period maximum clump height was recorded in *Dendrocalamus brandisii* (13.95,14.51 and 14,95m) followed by *Dendrocalamus longispathus* (13.32,13.70,14.41m) and *Dendrocalamus asper* (12.75,13.30 and 14.27m). *Bambusa tulda* consistently exhibited the lowest clump height in all four observation periods (9.58,9.87 and 10.45m).

Table 2: Clump height of different bamboo species at seventh year of growth (October 2022- October 2023) at Vellanikkara, Thrissur

Species	Clump height (m)			
	October 2022	February 2023	June 2023	October 2023
Bambusa vulgaris	11.67^{ab}	11.87^{ab}	12.62^{a}	12.83
Bambusa balcooa	11.85^{ab}	12.02^{ab}	12.65^{a}	12.75
Bambusa tulda	9.25^{b}	9.58^{b}	9.87^{b}	10.45
Dendrocalamus brandisii	13.77^{a}	13.95^{a}	14.51^{a}	14.95
Dendrocalamus asper	12.05^{a}	12.75^{a}	13.30^{a}	14.27
Dendrocalamus longispathus	12.90^{a}	13.32^{a}	13.70^{a}	14.41
P value	0.05	0.05	0.03	NS
C.D (0.05)	2.75	2.84	2.66	

Within a column, means having same letters as superscripts are homogeneous

4.1.2. Culm girth (cm)

The variation in culm girth of different bamboo species during four observational period is presented in Table 3. The culm girth shown a significant difference among different bamboo species. During first observation maximum culm girth was observed in *Bambusa vulgaris* (21.96 cm) which was found to be significantly higher over other species. However, the lowest culm girth was observed in *Bambusa tulda* (12.14 cm). While *Dendrocalamus brandisii* (20.04cm), *Dendrocalamus asper* (19.31cm) and *Bambusa balcooa* (19.62cm) observed intermediate culm girth which was significantly at par. Similarly, during second, third and fourth observation period, maximum culm girth was recorded in *Bambusa vulgaris* (22.40, 22.41, 22.71cm) followed by *Dendrocalamus brandisii* (20.60, 21.07, 22.21cm) and *Dendrocalamus asper* (19.9, 20.57 and 21.01cm). Throughout all four observation periods, *Bambusa tulda* was consistently with the lowest culm girth (12.80, 12.89, 13.58cm).

Table 3: Culm girth of different bamboo species at seventh year of growth (October 2022- October 2023) at Vellanikkara, Thrissur

Species	**Culm girth (cm)**			
	October 2022	February 2023	June 2023	October 2023
Bambusa vulgaris	21.96^{a}	22.40^{a}	22.41^{a}	22.71^{a}
Bambusa balcooa	19.62^{b}	19.76^{b}	20.02^{b}	20.33^{c}
Bambusa tulda	12.14^{d}	12.80^{d}	12.89^{d}	13.58^{e}
Dendrocalamus brandisii	20.04^{b}	20.60^{b}	21.07^{ab}	22.21^{ab}
Dendrocalamus asper	19.31^{b}	19.99^{b}	20.57^{b}	21.01^{bc}
Dendrocalamus longispathus	14.05^{c}	14.71^{c}	14.73^{c}	15.61^{d}
P value	<0.01	<0.01	<0.01	<0.01
C.D(0.05)	1.32	1.71	1.71	1.65

Within a column, means having same letters as superscripts are homogeneous

4.1.3. Number of culms per clump

The number of culms per clump among the different bamboo species during four observational periods is presented in Table 4. Under present investigation, the maximum number of culms per clump during first observation was observed in *Dendrocalamus asper* (55.75) which was statistically at par with *Bambusa tulda* (47.25) and *Dendrocalamus longispathus* (47). Conversely the lowest number of culms per clump was observed in *Bambusa balcooa* (15.75). whereas *Bambusa vulgaris* (32.50) and *Dendrocalamus brandisii* (28.75) showed the intermediate number of culms per clumps. Similarly, during second, third and fourth observation period maximum number of culms per clumps was again recorded in *Dendrocalamus asper* (55, 55.25, and 56.25) followed by *Bambusa tulda* (46.50, 46.50, 49.50) *and Dendrocalamus longispathus* (45.50, 47.75,48.25). Throughout all four observation periods, *Bambusa balcooa* consistently displayed the lowest number of culms per clump (15.75, 17.00, 17.50).

Table 4: Number of culms per clump of different bamboo species at seventh year of growth (October 2022- October 2023) at Vellanikkara, Thrissur

Species	**Number of culms per clump**			
	October 2022	February 2023	June 2023	October 2023
Bambusa vulgaris	32.50^{bc}	31.00^{bc}	33.25^{bc}	34.50^{bc}
Bambusa balcooa	15.75^{c}	15.75^{c}	17.00^{c}	17.50^{c}
Bambusa tulda	47.25^{ab}	46.50^{ab}	46.50^{ab}	49.50^{ab}
Dendrocalamus brandisii	28.75^{bc}	28.00^{bc}	32.75^{bc}	31.75^{bc}
Dendrocalamus asper	55.75^{a}	55.00^{a}	55.25^{a}	56.25^{a}
Dendrocalamus longispathus	47.00^{ab}	45.50^{ab}	47.75^{ab}	48.25^{ab}
P value	<0.01	<0.01	0.01	0.013
C.D(0.05)	21.25	20.00	20.01	21.44

Within a column, means having same letters as superscripts are homogeneous

4.1.4. Clump circumference (m)

The variation in clump circumference of different bamboo species during four observational periods is presented in Table 5. The clump circumference shown variation among different species, but the variation was not statistically significant. The clump circumference ranged from 4.50m to 5.75m during first observation period. During first observation, maximum clump circumference was observed in *Bambusa vulgaris* (5.75 m) followed by *Dendrocalamus asper* (5.02m) and *Bambusa tulda* (5.00m). However, the lowest clump circumference was observed in *Bambusa balcooa* (4.50m). In subsequent observational periods (second, third, and fourth), *Bambusa vulgaris* consistently showed the highest clump circumference (5.81, 6.43 and 6.47m) closely followed by *Dendrocalamus asper* (5.08,5.46 and 5.62m). The lowest clump circumference during second, third and fourth observation period was recorded under *Dendrocalamus brandisii* (4.89, 4.90, 5.01m).

Table 5: Clump circumference of different bamboo species at seventh year of growth (October 2022- October 2023) at Vellanikkara, Thrissur

Species	**Clump circumference (m)**			
	October 2022	February 2023	June 2023	October 2023
Bambusa vulgaris	5.75	5.81	6.43	6.47
Bambusa balcooa	4.50	4.96	5.53	5.95
Bambusa tulda	5.00	5.12	5.21	5.53
Dendrocalamus brandisii	4.86	4.89	4.90	5.01
Dendrocalamus asper	5.02	5.08	5.46	5.62
Dendrocalamus longispathus	4.84	4.94	5.03	5.16
P value	NS	NS	NS	NS

Within a column, means having same letters as superscripts are homogeneous

4.1.5. Internodal length (cm)

The variation in internodal length of different bamboo species during four observational periods is presented in Table 6. The internodal length shown a significant difference among different bamboo species. During first observation maximum internodal length was observed in *Dendrocalamus brandisii* (42.95 cm) which was found to be significantly higher over other species. The second highest internodal length was observed in *Dendrocalamus longispathus* (39.83cm) which was statistically at par with *Dendrocalamus asper* (39.40cm). However, the lowest internodal length was observed in *Bambusa tulda* (19.21 cm). Similarly, during second, third and fourth observation period maximum internodal length was recorded in *Dendrocalamus brandisii* (43.04, 43.85, 44.01cm) followed by *Dendrocalamus longispathus* (39.85, 39.82, 40.34cm). Throughout all four observation periods, *Bambusa tulda* consistently displayed the lowest internodal length (19.33, 19.41 and 19.66cm).

Table 6: Internodal length of different bamboo species at seventh year of growth (October 2022- October 2023) at Vellanikkara, Thrissur

Species	**Internodal length (cm)**			
	October 2022	February 2023	June 2023	October 2023
Bambusa vulgaris	30.74^{c}	30.87^{c}	30.90^{c}	30.94^{c}
Bambusa balcooa	23.44^{d}	23.77^{d}	24.75^{d}	25.18^{d}
Bambusa tulda	19.21^{e}	19.33^{e}	19.41^{e}	19.66^{e}
Dendrocalamus brandisii	42.95^{a}	43.04^{a}	43.85^{a}	44.01^{a}
Dendrocalamus asper	39.40^{b}	39.52^{b}	40.55^{b}	41.27^{b}
Dendrocalamus longispathus	39.83^{b}	39.85^{b}	39.82^{b}	40.34^{b}
P value	<0.01	<0.01	<0.01	<0.01
C.D(0.05)	2.35	2.47	2.28	2.29

Within a column, means having same letters as superscripts are homogeneous

4.2. Litter dynamics

Litter quantification, decomposition pattern and nutrient release dynamics of six bamboo species was studied for one year period and the results are presented in detail in the subsequent section.

4.2.1. Litterfall quantity:

The data related to litter quantification in selected six bamboo species for the period spanning October,2022 to September 2023 (six years old) are presented in Table 7 and Fig. 3 and 4. The production of litter among six selected bamboo species at different months varied significantly.

The analysis of data revealed that the annual litter production calculated by summing the monthly litter production during October,2022 september,2023, amounted to 9.64, 6.98, 7.3, 7.8, 8.05 and 9.59 Mg ha^{-1} $year^{-1}$ in *Bambusa vulgaris, Bambusa balcooa, Bambusa tulda, Dendrocalamus brandisii, Dendrocalamus asper, Dendrocalamus longispathus* respectively (Fig.4). The trend of annual litter production among different species was in following order ***Bambusa vulgaris* > *Dendrocalamus longispathus*> *Dendrocalamus asper* > *Dendrocalamus brandisii* > *Bambusa tulda* > *Bambusa balcooa*.**

The litter production in *Bambusa vulgaris* showed statistically significant variation across different months and maximum amount of litterfall was observed in the month of December accounting 22.51% of total annual litter production. Litterfall exhibited bimodal pattern with major peak observed followed by N-E monsoon i.e., December and minor peak followed by S-W monsoon i.e., in July. In *Bambusa balcooa*, highest amount of litter fall was observed in the month of December (20.20%). The litter fall exhibited trimodal pattern with major peak in December and two minor peaks in February and July.

The highest litterfall in *Bambusa tulda* was recorded during the month of January, accounting for 14.66% of the total litterfall. The litterfall displayed a bimodal pattern, with a significant major peak in January and a minor peak in July.

Meanwhile, in *Dendrocalamus brandisii* highest litterfall was recorded during month of January, according for 17.26% of total litterfall. The litterfall displayed a bimodal pattern, with a significant major peak in January and a smaller minor peak in July.

The highest litterfall in *Dendrocalamus asper* was recorded in the month of January, accounting for 16.24% of the total litterfall. The litterfall displayed a bimodal pattern, with a significant major peak in January and a minor peak in June.

Interestingly, the highest litterfall *in Dendrocalamus longispathus* was recorded in the month of February, accounting for 17.73% of the total litterfall. The litterfall displayed a bimodal pattern, with a significant major peak in February and a minor peak in July. From table 7 it is quite visible that maximum amount of litter production in all selected species occurred between November to February.

Table 7: Variation in monthly litter production of different bamboo species at seventh year of growth at Vellanikkara, Thrissur

Months	Monthly litter production (Mg ha $^{-1}$)						C.D (0.05)
	Bambusa vulgaris	*Bambusa balcooa*	*Bambusa tulda*	*Dendrocalamus brandisii*	*Dendrocalamus asper*	*Dendrocalamus longispathus*	
October	1.01_{c}^{A}	0.44_{def}^{B}	0.43_{de}^{B}	0.86_{c}^{A}	0.41_{fg}^{B}	0.37_{f}^{B}	0.28
November	1.32_{b}^{A}	0.45_{def}^{CD}	0.76_{c}^{BC}	0.87_{bc}^{B}	0.74_{cde}^{BC}	0.34_{f}^{D}	0.34
December	2.17_{a}^{A}	1.41_{a}^{B}	0.89_{bc}^{C}	1.19_{ab}^{BC}	0.90_{bc}^{C}	1.19_{b}^{BC}	0.45
January	0.87_{cd}^{BC}	0.82_{c}^{C}	1.26_{a}^{ABC}	1.29_{a}^{AB}	1.29_{a}^{AB}	1.68_{a}^{A}	0.46
February	0.82_{cde}^{CD}	1.05_{b}^{BC}	1.07_{ab}^{B}	0.59_{cde}^{D}	1.06_{ab}^{B}	1.70_{a}^{A}	0.24
March	0.73_{de}^{BC}	0.62_{cd}^{C}	0.65_{cd}^{C}	0.42_{def}^{D}	0.82_{bcd}^{AB}	0.94_{c}^{A}	0.15
April	0.62_{def}^{A}	0.45_{def}^{B}	0.38_{de}^{BC}	0.32_{ef}^{C}	0.59_{def}^{A}	0.68_{de}^{A}	0.13
May	0.59_{ef}^{A}	0.37_{efg}^{B}	0.31_{e}^{B}	0.27_{f}^{B}	0.56_{ef}^{A}	0.65_{de}^{A}	0.14
June	0.44_{fg}^{B}	0.44_{def}^{B}	0.39_{de}^{B}	0.45_{def}^{B}	0.70_{cde}^{A}	0.51_{ef}^{B}	0.16
July	0.58_{ef}^{BC}	0.54_{de}^{BC}	0.62_{cd}^{AB}	0.69_{cd}^{AB}	0.41_{fg}^{C}	0.81_{cd}^{A}	0.2
August	0.27_{g}^{BC}	0.23_{fg}^{C}	0.24_{e}^{C}	0.49_{def}^{A}	0.32_{g}^{BC}	0.42_{f}^{AB}	0.16
September	0.22_{g}^{BC}	0.16_{g}^{C}	0.30_{e}^{AB}	0.36_{ef}^{A}	0.25_{g}^{BC}	0.30_{f}^{AB}	0.1
Total	**9.64**	**6.98**	**7.3**	**7.8**	**8.05**	**9.59**	
C.D(0.05)	0.26	0.22	0.28	0.32	0.24	0.21	

With in row, means having same uppercase letters as superscript are homogeneous (significant at 1% level). Within column, means having same lowercase letters as subscripts are homogeneous (significant at 1% level)

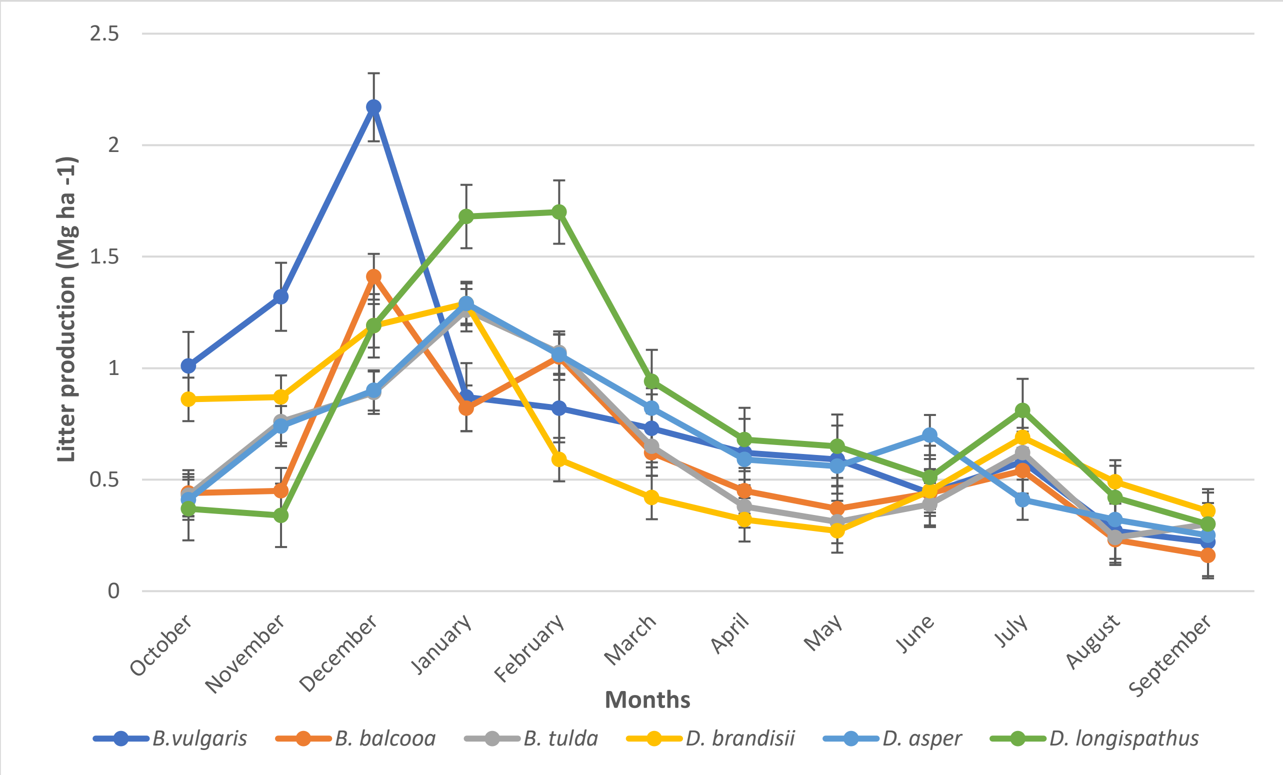


Fig 3. Monthly litter production under selected six bamboo species during October,2022 to September,2023 at Vellanikkara, Thrissur

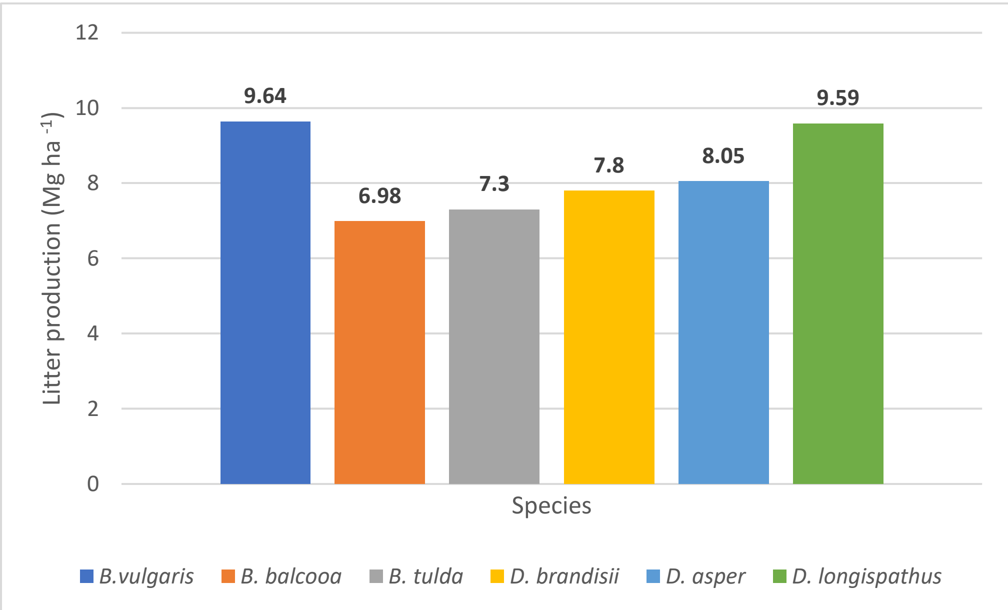


Fig 4. Annual litter production of different bamboo species at seventh year of growth at Vellanikkara, Thrissur

4.2.2. Litter composition

The data related to the percentage composition of annual litter mass in selected six bamboo species is illustrated in Fig 5. In almost all the six bamboo species leaf contributed highest (>70%) towards the total litter mass. However, twigs also formed an important component of litter in all species. The contribution of twigs to total litterfall ranged from 16.1% (*Bambusa vulgaris*) to 25.44% (*Dendrocalamus brandisii*). The contribution of sheath to total litterfall ranged from 5.9% (*Bambusa tulda*) to 12.04% (*Dendrocalamus asper*). The percentage contribution of litter components was in following order **leaf > twigs > sheath.**

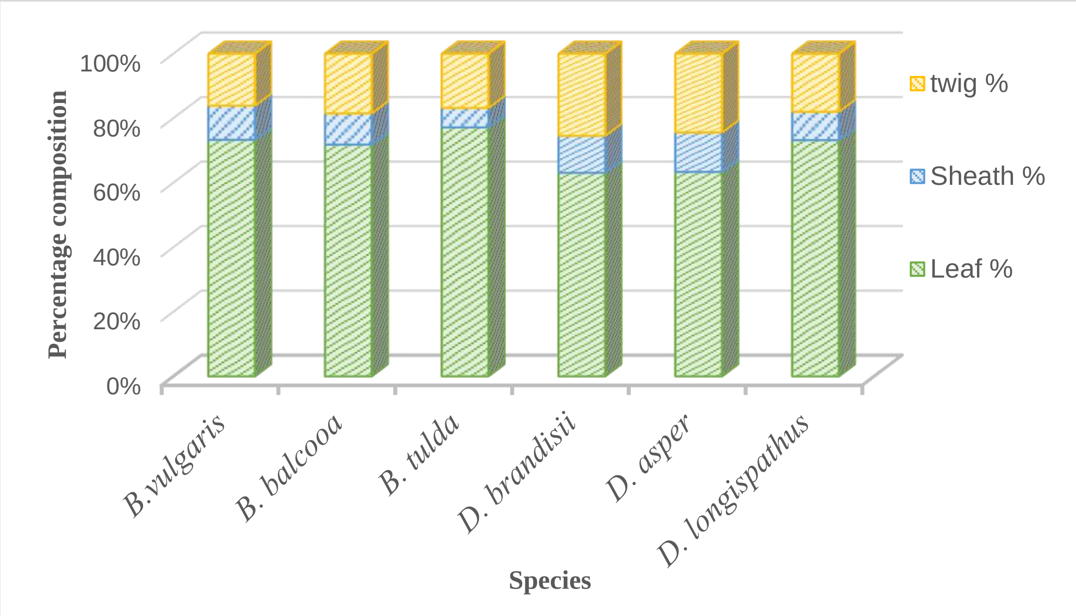


Fig 5. Percentage composition of litter mass among different bamboo species at Vellanikkara, Thrissur

4.2.3. Litter decomposition

The data related to litter decomposition and mass loss in six different bamboo species for the period spanning October 2022 to September 2023 (six years old) are presented in Table 8 and 9. The mass loss in decomposing litter varied significantly among the bamboo species. Almost all species has followed a triphasic pattern of litter decomposition i.e., rate of litter mass loss was rapid in in the first month of decomposition in all bamboo species but slowed down in later months

Table 8: Residual mass remaining (g) in the litter of bamboo species at different stages of decomposition at Vellanikkara, Thrissur

Months	**Residual litter mass remaining (g)**						C.D (0.05)
	Bambusa vulgaris	*Bambusa balcooa*	*Bambusa tulda*	*Dendrocalamus brandisii*	*Dendrocalamus asper*	*Dendrocalamus longispathus*	
Initial	20.00_{a}	20.00_{a}	20.00_{a}	20.00_{a}	20.00_{a}	20.00_{a}	NS
October	15.64_{b}^{BC}	16.78_{b}^{ABC}	15.06_{b}^{C}	17.84_{ab}^{A}	16.93_{b}^{AB}	16.49_{b}^{ABC}	1.78
November	15.23_{b}^{AB}	16.47_{bc}^{AB}	14.47_{bc}^{C}	17.17_{b}^{A}	15.33_{bc}^{BC}	15.77_{bc}^{ABC}	1.60
December	14.31_{bc}^{AB}	14.1_{cd}^{AB}	12.05_{bc}^{B}	16.45_{bc}^{A}	14.75_{bcd}^{AB}	15.70_{bc}^{A}	3.10
January	12.39_{cd}^{A}	13.81_{d}^{A}	11.91_{bc}^{A}	14.30_{cd}^{A}	14.09_{cde}^{A}	15.38_{bcd}^{A}	3.96
February	12.13_{cd}^{CD}	12.52_{de}^{BCD}	11.31_{cd}^{D}	14.10_{cd}^{AB}	13.52_{cde}^{ABC}	14.57_{cd}^{A}	1.59
March	11.41_{d}^{B}	11.07_{ef}^{B}	8.27_{de}^{C}	13.77_{de}^{A}	12.42_{de}^{AB}	13.88_{d}^{A}	2.29
April	10.27_{de}^{AB}	9.98_{fg}^{AB}	7.73_{e}^{B}	11.77_{def}^{A}	11.56_{e}^{A}	11.20_{e}^{A}	3.28
May	9.00_{ef}^{AB}	8.96_{fg}^{AB}	6.68_{ef}^{B}	11.30_{ef}^{A}	8.78_{f}^{AB}	9.94_{ef}^{AB}	3.80
June	7.38_{fg}^{B}	8.14_{gh}^{AB}	4.26_{fg}^{C}	10.61_{fg}^{A}	7.49_{fg}^{B}	9.37_{f}^{AB}	2.55
July	6.50_{gh}^{AB}	7.71_{gh}^{A}	3.63_{fg}^{B}	8.13_{g}^{A}	5.16_{g}^{AB}	6.84_{g}^{AB}	3.22
August	4.9_{h}^{ABC}	6.39_{h}^{A}	2.88_{gh}^{BC}	5.42_{h}^{AB}	2.24_{h}^{C}	5.94_{g}^{A}	3.00
September	2.44_{i}^{A}	3.27_{i}^{A}	0.12_{h}^{B}	2.93_{h}^{A}	1.88_{h}^{AB}	2.89_{h}^{A}	1.86
C.D(0.05)	2.27	2.37	3.38	2.55	2.63	1.80	

With in row, means having same uppercase letters as superscript are homogeneous (significant at 5% level). Within column, means having same lowercase letters as subscripts are homogeneous (significant at 1% level)

Table 9: Residual mass remaining (%) in the litter of different bamboo species at different stages of decomposition at Vellanikkara, Thrissur

Months	Residual litter mass remaining (%)					
	Bambusa vulgaris	*Bambusa balcooa*	*Bambusa tulda*	*Dendrocalamus brandisii*	*Dendrocalamus asper*	*Dendrocalamus longispathus*
Initial	100.00 (0)	100.00 (0)	100.00 (0)	100.00 (0)	100.00 (0)	100.00 (0)
October	78.20 (21.80)	83.90 (16.10)	75.30 (24.7)	89.20 (10.80)	84.65 (15.35)	82.45 (17.55)
November	76.15 (23.85)	82.35 (17.65)	72.35 (27.65)	85.85 (14.15)	76.65 (23.35)	78.85 (21.15)
December	71.55 (28.45)	70.50 (29.50)	60.25 (39.75)	82.25 (17.75)	73.75 (26.25)	78.50 (21.50)
January	61.95 (38.05)	69.05 (30.95)	59.55 (40.45)	71.50 (28.50)	70.45 (29.55)	76.90 (23.10)
February	60.65 (39.35)	62.60 (37.4)	56.55 (43.45)	70.50 (29.50)	67.60 (32.40)	72.85 (27.15)
March	57.05 (42.95)	55.35 (44.65)	41.35 (58.65)	68.85 (31.15)	62.10 (37.90)	69.40 (30.60)
April	51.35 (48.65)	49.90 (50.10)	38.65 (61.35)	58.85 (41.15)	57.80 (42.20)	56.00 (44.00)
May	45.00 (55.00)	44.80 (55.2)	33.40 (66.60)	56.50 (43.50)	43.90 (56.10)	49.70 (50.30)
June	36.90 (63.10)	40.70 (59.30)	21.30 (78.70)	53.05 (46.95)	37.45 (62.55)	46.85 (53.15)
July	32.50 (67.50)	38.55 (61.45)	18.15 (81.85)	40.65 (59.35)	25.80 (74.20)	34.20 (65.80)
August	24.50 (75.50)	31.95 (68.05)	14.40 (85.60)	27.10 (72.90)	11.20 (88.80)	29.70 (70.30)
September	12.20 (87.80)	16.35 (83.65)	0.60 (99.40)	14.65 (85.35)	9.40 (90.60)	14.45 (85.55)

Values in parenthesis indicate percentage mass loss of the litter and again, showed a rapid mass loss towards end of the study. During the course of the study out of six bamboo species only *Bambusa tulda* has almost decomposed completely (99.4%) while rest of species decomposed only up to 85-90%. Mass remained at the end of 12 months (% of initial mass) period was: *Bambusa vulgaris* (12.2%), *Bambusa balcooa* (16.35%), *Dendrocalamus brandisii* (14.65%), *Dendrocalamus asper* (9.4%), *Dendrocalamus longispathus* (14.45%).

Regression analysis (Table 10) was employed to establish the relationship between the duration of incubation and the extent of litter decomposition. Litter mass, presented as a percentage of the initial dry mass, exhibited an exponential decrease over time. Therefore, the mass loss data was fitted with the negative exponential model, represented by the equation $y = e^{-kt}$ as recommended by Olson (1963). Figures 6-11 illustrate the litter mass loss patterns for six bamboo species. All the exponential regression equations utilized to characterize mass loss over time were found to be statistically significant (1% level). The rates of decomposition in the six bamboo species were well-suited to the exponential decay model proposed by Olson (1963).

Table 10: Exponential regression equations obtained for the decomposing litter of bamboo species at Vellanikkara, Thrissur

Species	**Exponential regression equation**	**Coefficient of determination(R^2)**
Bambusa vulgaris	$y= 4.69e^{-0.136x}$	0.863
Bambusa balcooa	$y= 4.66e^{-0.123x}$	0.895
Bambusa tulda	$y= 5.04e^{-0.292x}$	0.638
Dendrocalamus brandisii	$y= 4.48e^{-0.127x}$	0.797
Dendrocalamus asper	$y= 4.87e^{-0.196x}$	0.814
Dendrocalamus longispathus	$y= 4.75e^{-0.126x}$	0.823

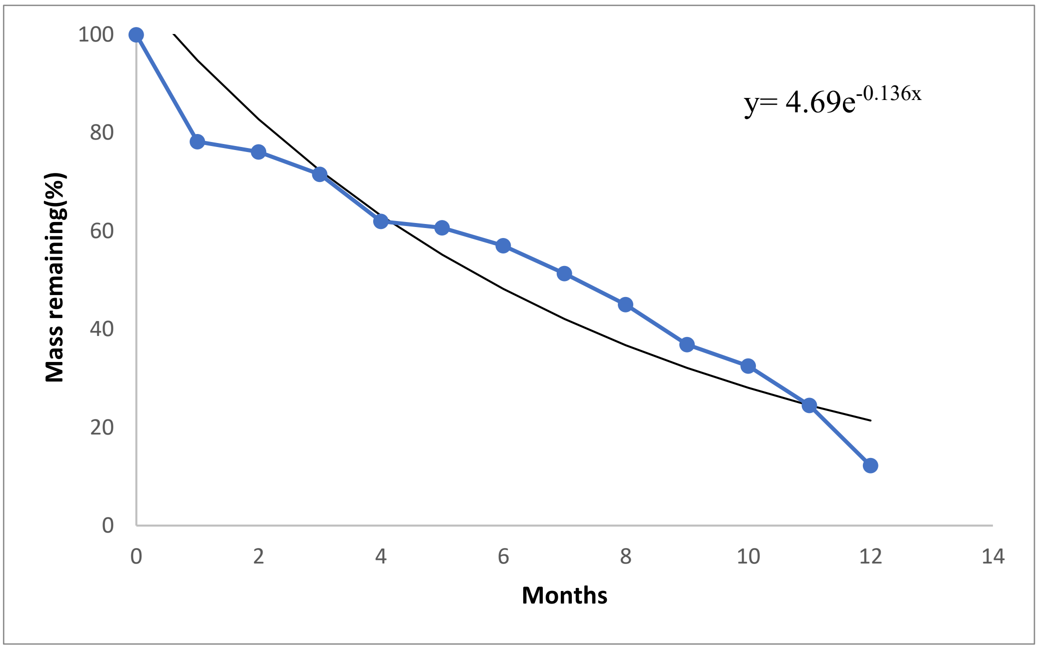


Fig 6. Litter decomposition of *Bambusa vulgaris* (blue line represent actual mass loss and black line represent the predicted mass loss from exponential model) at Vellanikkara, Thrissur

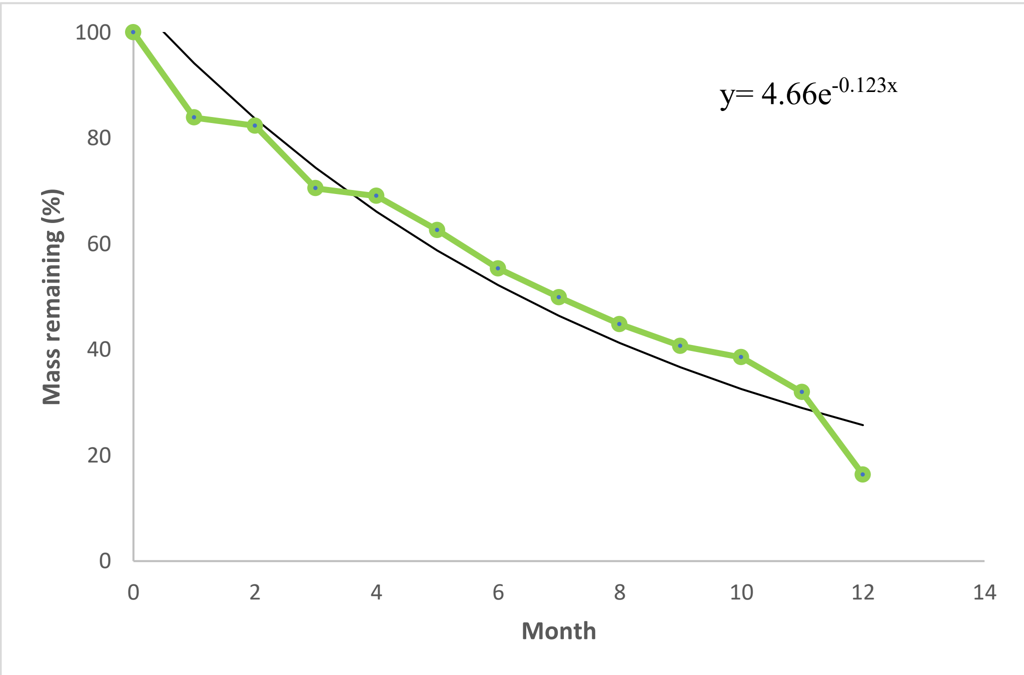


Fig 7. Litter decomposition of *Bambusa balcooa* (green line represent actual mass loss and black line represent the predicted mass loss from exponential model) at Vellanikkara, Thrissur

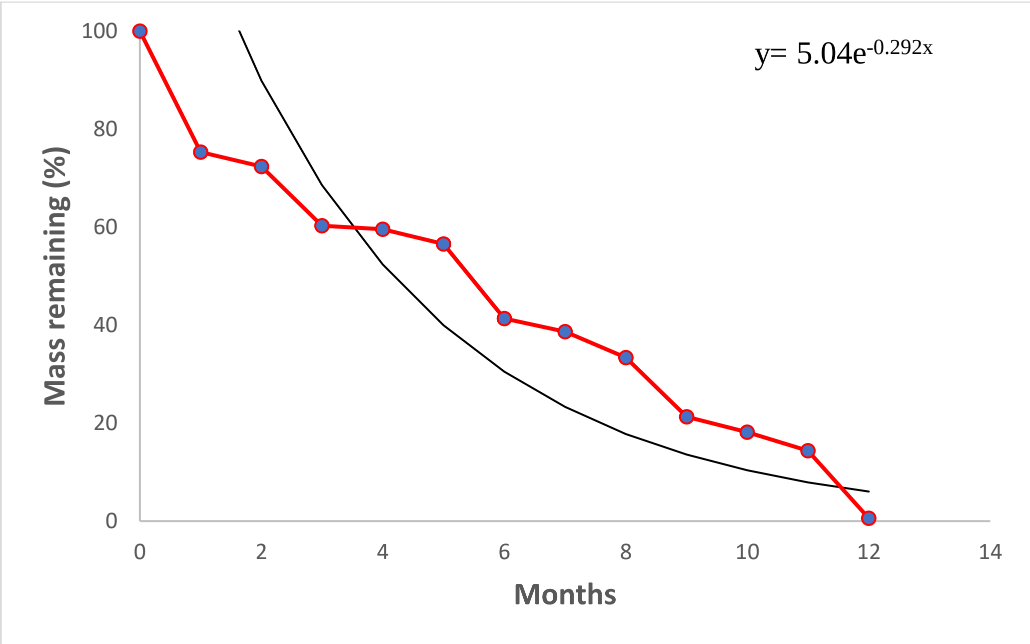


Fig 8. Litter decomposition of *Bambusa tulda* (red line represent actual mass loss and orange line represent the predicted mass loss from exponential model) at Vellanikkara, Thrissur

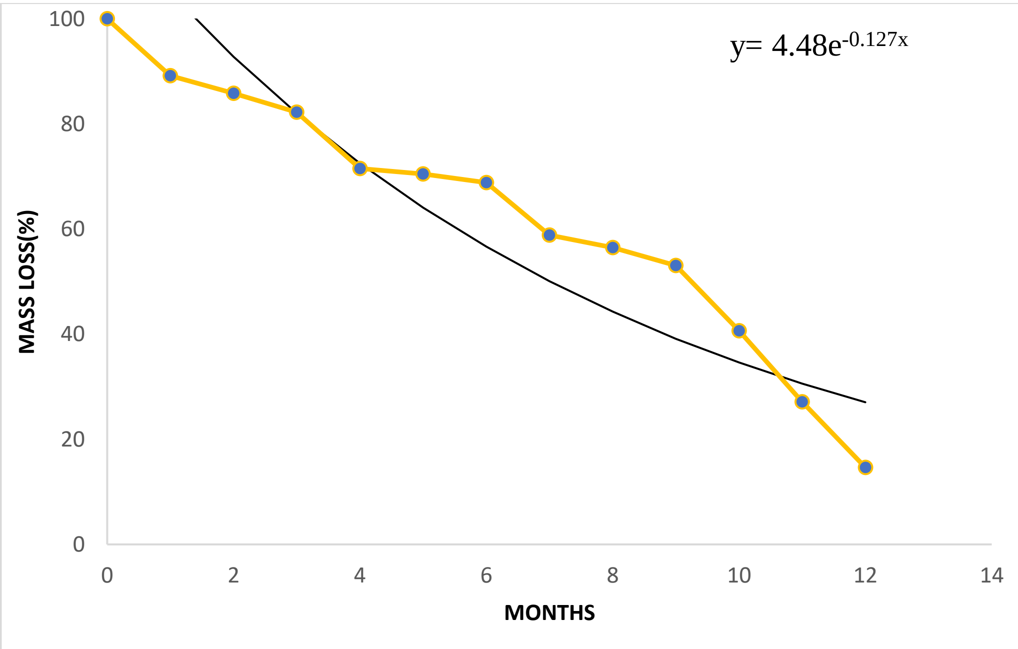


Fig 9. Litter decomposition of *Dendrocalamus brandisii* (yellow line represent actual mass loss and black line represent the predicted mass loss from exponential model) at Vellanikkara, Thrissur

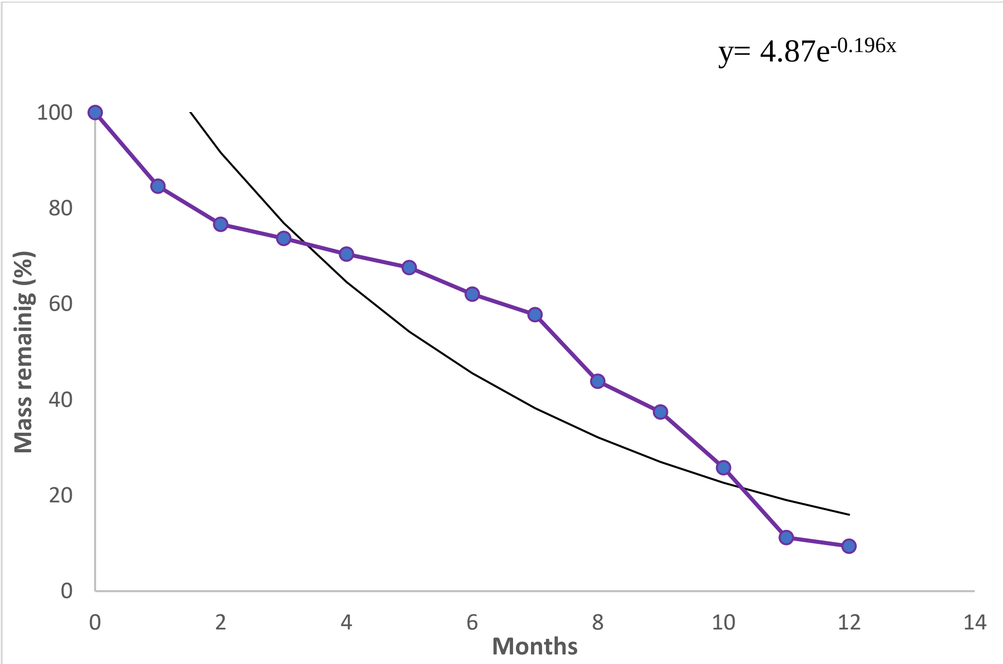


Fig 10. Litter decomposition of *Dendrocalamus asper* (violet line represent actual mass loss and black line represent the predicted mass loss from exponential model) at Vellanikkara, Thrissur

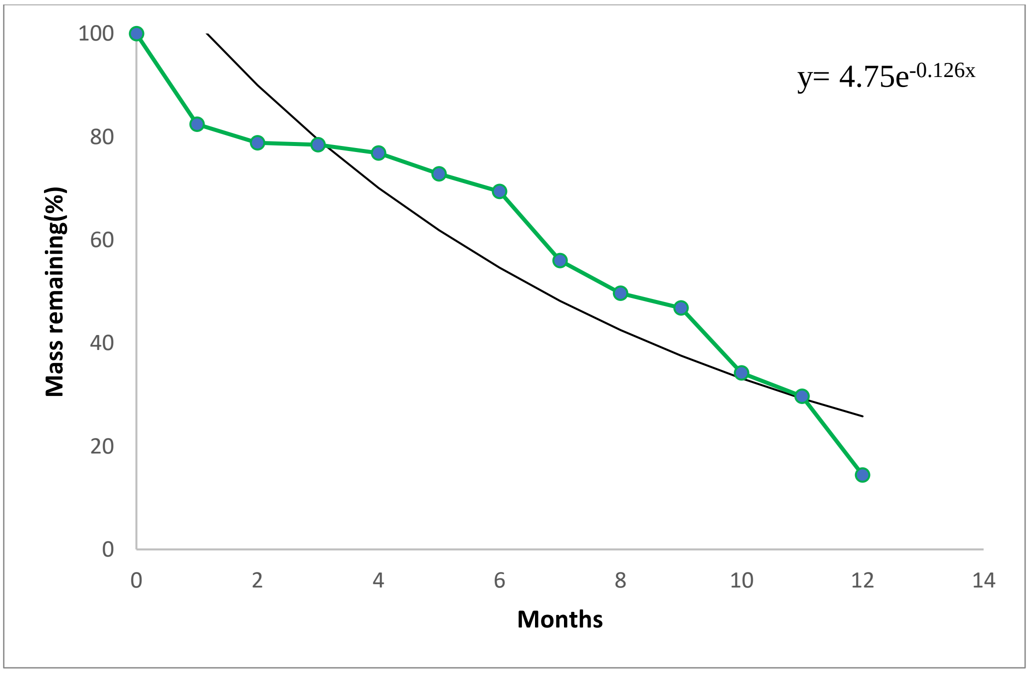


Fig 11. Litter decomposition of *Dendrocalamus longispathus* (green line represent actual mass loss and black line represent the predicted mass loss from exponential model) at Vellanikkara, Thrissur

The decay rate coefficient (k) and half-life of decomposing litter of different bamboo species are given in Table 11. Highest k value was recorded in *Bambusa tulda* (0.292 month^{-1}) and the lowest k value was recorded in *Bambusa balcooa* (0.123 month^{-1}). The rate of litter decomposition in different bamboo species was in following order ***Bambusa tulda* > *Dendrocalamus asper* > *Bambusa vulgaris* > *Dendrocalamus brandisii* > *Dendrocalamus longispathus* >*Bambusa balcooa***. Also, the time taken to reach half of initial quantity was observed highest in *Bambusa balcooa* (5.75 months) and lowest values was observed under *Bambusa tulda* (2.42 months).

Table 11: Decomposition rate coefficient and half-life period corresponding to litter of different bamboo species at Vellanikkara, Thrissur

Species	**k (month $^{-1}$)**	**Half-life in months ($t_{0.5}$)**
Bambusa vulgaris	0.136 ^{bc}	5.13 ^{ab}
Bambusa balcooa	0.123 ^{c}	5.75 ^{a}
Bambusa tulda	0.292 ^{a}	2.42 ^{c}
Dendrocalamus brandisii	0.127 ^{c}	5.58 ^{a}
Dendrocalamus asper	0.196 ^{b}	3.75 ^{bc}
Dendrocalamus longispathus	0.126 ^{c}	5.56 ^{a}
C.D(0.05)	0.06	1.59
P value	<0.01	<0.01

Within a column, means having same letters as superscripts are homogeneous

4.2.4. Nutrient release dynamics of decomposing litter

The subsequent section presents the nutrient release pattern of litter during the decomposition process in the six selected bamboo species.

4.2.4.1. Initial litter nutrient content

The initial nitrogen, phosphorus, and potassium concentration in litter of different bamboo species is presented in table 12. The analysis of data revealed statistically significant differences in initial litter nitrogen, phosphorus, and potassium concentrations among different species. The initial litter nitrogen of selected bamboo species ranged between 1.27 to 2.42%. The highest nitrogen content was observed under *Bambusa tulda*

(2.42%) and lowest under the *Dendrocalamus brandisii* (1.27%). The trend of initial nitrogen concentration among different bamboo species was in following order ***Bambusa tulda* > *Bambusa balcooa* > *Bambusa vulgaris* > *Dendrocalamus longispathus* > *Dendrocalamus asper* > *Dendrocalamus brandisii.***

Table 12: Initial nutrient concentration in six different bamboo litter at Vellanikkara, Thrissur

Species	Nitrogen (%)	Phosphorus (%)	Potassium (%)	Carbon (%)	C:N ratio
Bambusa vulgaris	1.83^{b}	0.048^{b}	0.40^{ab}	49.36^{a}	27.32^{b}
Bambusa balcooa	1.87^{b}	0.044^{b}	0.32^{bc}	48.59^{a}	26.14^{b}
Bambusa tulda	2.42^{a}	0.091^{a}	0.47^{a}	48.33^{a}	20.02^{c}
Dendrocalamus brandisii	1.27^{c}	0.043^{b}	0.28^{bc}	46.21^{b}	36.53^{a}
Dendrocalamus asper	1.59^{bc}	0.035^{b}	0.41^{ab}	45.69^{b}	28.88^{b}
Dendrocalamus longispathus	1.64^{bc}	0.060^{b}	0.22^{c}	46.46^{b}	29.17^{a}
C.D(0.05)	0.38	0.025	0.14	1.46	5.82
P value	<0.01	<0.01	0.05	<0.01	<0.01

The values with same superscripts within column do not varies significantly

The initial phosphorus content in the litter of the selected bamboo species ranged from 0.091 to 0.035%. The highest phosphorus content was observed in *Bambusa tulda* (0.091%) and lowest under the *Dendrocalamus asper* (0.035%). The trend of initial phosphorus concentration among different bamboo species was in following order ***Bambusa tulda* > *Dendrocalamus longispathus*> *Bambusa vulgaris* > *Bambusa balcooa*> *Dendrocalamus brandisii* >*Dendrocalamus asper***. While the potassium concentration in initial litter of the selected bamboo species ranged from 0.44 to 0.22%. The highest potassium concentration was observed in *Bambusa tulda* (0.47%) and lowest under the *Dendrocalamus longispathus* (0.22%). The trend of initial potassium concentration among different bamboo species was in following order ***Bambusa tulda* >**

***Dendrocalamus asper* > *Bambusa vulgaris* > *Bambusa balcooa*> *Dendrocalamus brandisii* > *Dendrocalamus longispathus*.** The C:N ratio in initial litter of six bamboo species ranged from 20.02 to 36.53. The highest C:N ratio was observed in *Dendrocalamus brandisii* (36.53) and lowest under the *Bambusa tulda* (20.02).

4.2.4.2. Concentration of nutrients in decomposing litter

Figure 12 to 14 illustrates the percentage concentration of nutrients in the litter mass collected at various stages of decomposition for *Bambusa vulgaris, Bambusa balcooa, Bambusa tulda, Dendrocalamus brandisii, Dendrocalamus asper, Dendrocalamus longispathus*. As the process of decomposition proceeds nutrient concentration in litter varied significantly among the selected bamboo species.

4.2.4.2.1. Nitrogen

Nitrogen constituted the largest proportion of litter mass among the three major nutrients that were assessed in the study**.** The analysis of data shows that concentration of nitrogen varied significantly among decomposing litter of different species with time. In case of *Bambusa vulgaris* the nitrogen concentration varied from 1.83% to 0.43%. Initially, the nitrogen concentration in the decomposing litter was 1.83%, which experienced a notable decrease of 58.98% in the first month of decomposition. Over time, the nitrogen content continued to decline and reached its lowest point in April (210 days after incubation). Subsequently, from April to July (300 days after incubation), there was a gradual increase in nitrogen content. However, towards the later months, there was a slight reduction in nitrogen concentration. In case of *Bambusa balcooa* the nitrogen concentration varied from 1.87% to 0.43%. Initially, the nitrogen concentration in the decomposing litter was 1.87%, which experienced a notable decrease during the initial months of the decomposition process reaching its lowest point in February i.e.,150 days after incubation. Subsequently, from February to June slight fluctuation were there in nitrogen concentration. However, towards the later months (July-September), there was a slight reduction in nitrogen concentration.

In case of *Bambusa tulda* the nitrogen concentration varied from 2.42% to 0.67% during the various stages of decomposition. Initially, the nitrogen concentration in the decomposing litter was 2.42%, which experienced a notable decrease during the initial months of decomposition till December with exception in November. Subsequently, from January to February (150 days after incubation), there was a gradual increase in nitrogen content. However, after February a minor decrease in nitrogen levels was noted, with the lowest point being reached in June (270 days after incubation). Due to the rapid decomposition in *Bambusa tulda*, there was negligible amount of remaining litter toward the end of the study (September) for the analysis of nitrogen concentration.

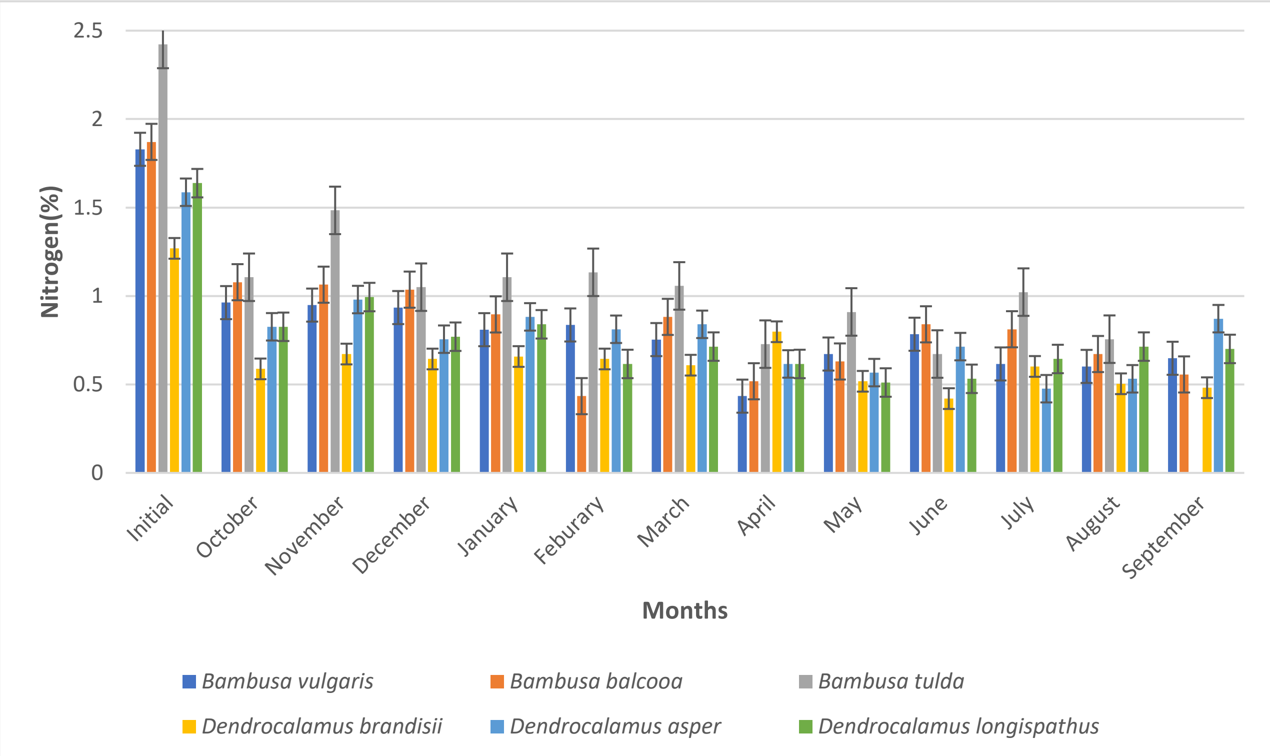


Fig. 12 Variation in Nitrogen concentration in the litter of different bamboo species during different decomposition stages at Vellanikkara, Thrissur

In case of *Dendrocalamus brandisii* the nitrogen concentration varied from 1.27% to 0.42% during the various stages of decomposition. Initially, the nitrogen concentration in the decomposing litter was 1.27% and it notably declined as the decomposition progressed, reaching its lowest level in June (270 days after incubation), with exception in November and April when slight increase in nitrogen concentration was observed. In case of *Dendrocalamus asper* the nitrogen concentration varied from 1.59% to 0.48%

during the various stages of decomposition. Initially, the nitrogen concentration in the decomposing litter was 1.59% and it notably declined as the decomposition progressed, reaching its lowest level in July (300 days after incubation), with exception in November, January, and march when slight increase in nitrogen concentration was observed. However, towards the later months (September), there was a slight increase in nitrogen concentration. In case of *Dendrocalamus longispathus* the nitrogen concentration varied from 1.64% to 0.53% during the various stages of decomposition. The initial nitrogen concentration in the decomposing litter was 1.64%, which significantly decrease as decomposition proceeded, ultimately reaching its lowest point in May (240 days after incubation). Following that, there was a gradual increase in nitrogen content from June to August (330 days post-incubation), after which the nitrogen concentration declined in September.

4.2.4.2.2. Phosphorus

The analysis of data shows that concentration of phosphorus varied significantly among decomposing litter of different species with time. In case of *Bambusa vulgaris* the phosphorus (P) concentration in the residual litter mass varied between 0.107% to 0.026% at different decomposition stages. Initially, the phosphorus concentration in the decomposing litter was 0.048%. It experienced a noticeable increase during the initial months of decomposition, reaching its peak in February (150 days). In the subsequent months, there was a slight decline in phosphorus concentration until June (270 days), where the lowest P concentration (0.029) was observed. However, starting from June, the P concentration began to increase significantly, reaching its highest value in August (330 days) at 0.107, nearly double the initial concentration. After August, the P concentration decreased again, but it remained higher than the initial concentration of 0.050. For *Bambusa balcooa*, the phosphorus (P) concentration in the remaining litter mass varied from 0.081% to 0.035% at different stages of decomposition. Similar to *Bambusa vulgaris, Bambusa balcooa* exhibited a comparable trend, with an initial increase in phosphorus concentration until February (150 days). In the following months, there was a slight decrease in phosphorus concentration until May (240 days), where the lowest P concentration (0.035) was observed. However, from May onwards, the P concentration significantly rose, reaching its peak in July (300 days) at 0.081, which is roughly double the initial concentration. Following July, the P concentration decreased again, although it remained higher (0.051) than the initial concentration of 0.044.

In the case of *Bambusa tulda*, the phosphorus (P) concentration in the residual litter mass ranged between 0.099% and 0.039% during different decomposition stages. Initially, the P concentration in the decomposing litter was 0.091%. It showed a notable decrease in the first month of decomposition, after which the P concentration began to increase until December (90 days). The lowest P concentration was observed in April (0.038), while the highest P concentration in the decomposing litter was recorded in August (0.099). Because of the rapid decomposition in *Bambusa tulda*, there was a negligible amount of remaining litter by the end of the study in September for the analysis of P concentration in that month.

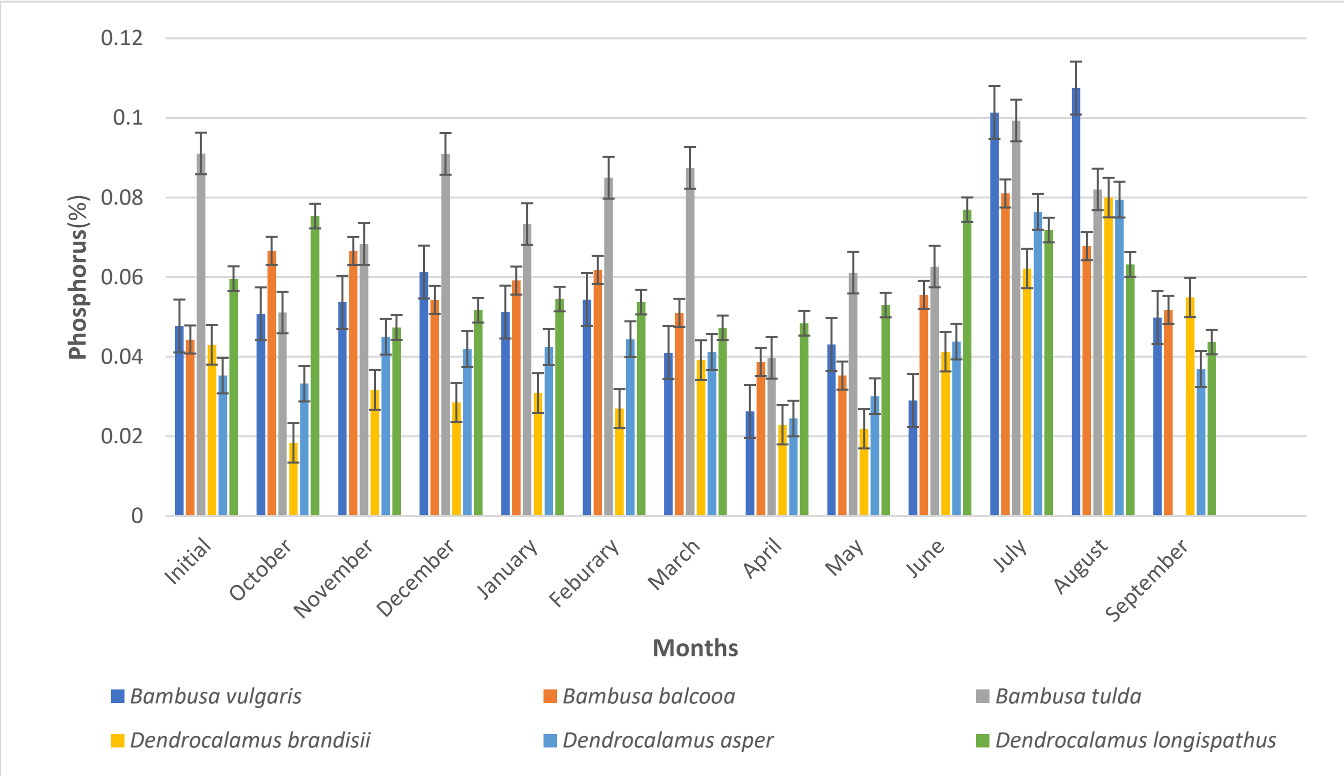


Fig.13. Variation in Phosphorus concentration in the litter of bamboo species during different decomposition stages at Vellanikkara, Thrissur

For *Dendrocalamus brandisii*, the phosphorus (P) concentration in the remaining litter mass varied from 0.080% to 0.018% across various stages of decomposition. Initially, the P concentration in the decomposing litter was 0.091%. There was a sharp decline in P concentration during the initial month of decomposition, marking the lowest concentration observed during the study period. Following this, the P concentration started to rise until March (180 days), except for December and February when the P concentration decreased. The highest P concentration was observed at the end of August (0.080), which was nearly double the initial concentration.

Dendrocalamus asper displayed a pattern similar to *Dendrocalamus brandisii*, characterized by an initial decline in phosphorus concentration during the first month of decomposition. Subsequently, there was a slight rise in phosphorus concentration in the following months until February (150 days). Afterward, the P concentration began to decrease in the litter, reaching its lowest point in April (0.024) and its highest concentration in August (0.079). For *Dendrocalamus longispathus*, the phosphorus (P) concentration in the remaining litter mass ranged from 0.077% to 0.044% across various stages of decomposition. Initially, the P concentration in the decomposing litter was 0.060%. It showed a significant rise during the initial months of decomposition. The peak concentration of P was recorded in June (0.077), while the lowest concentration was noted in September (0.044) i.e., 360 days after incubation.

4.2.4.2.3. Potassium:

Concentration of potassium in decomposing litter retrieved at different months is illustrated in Fig.14 The concentration of potassium varied greatly in the selected bamboo species with time. In case of *Bambusa vulgaris*, the potassium (K) concentration ranged from 0.401% to 0.025%. The highest K concentration was observed in the initial litter mass (0.401%). During the first month of decomposition, there was a significant reduction in K concentration, followed by a more gradual decline, leading to the lowest recorded value in April (0.025), 210 days after incubation. After April, the K concentration began to rise, reaching 0.065% in July, but again subsequently decreased to 0.045 in September.

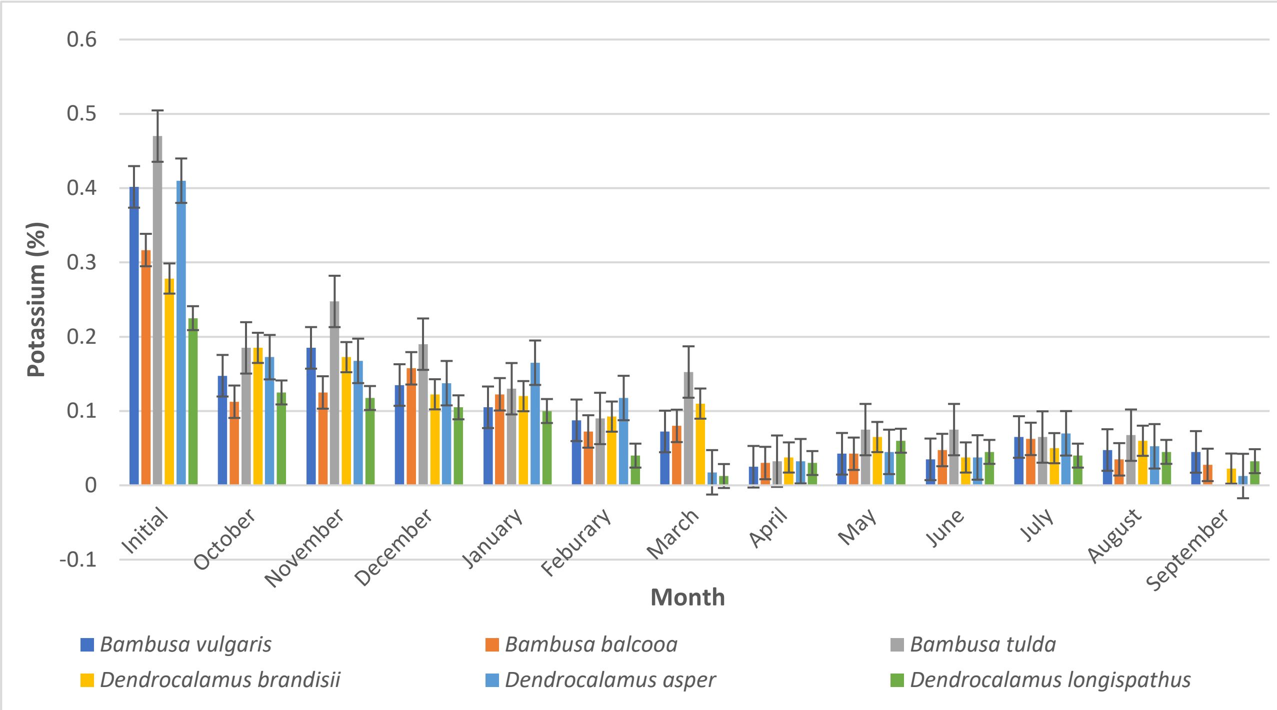


Fig.14. Variation in Potassium concentration in the litter of bamboo species during different decomposition stages at Vellanikkara, Thrissur

For *Bambusa balcooa*, the potassium concentration in the remaining litter mass varied from 0.317% to 0.03% at different stages of decomposition. Similar to *Bambusa vulgaris, Bambusa balcooa* also displayed a similar pattern, characterized by an initial sharp decrease in potassium (K) concentration, followed by a slower rate of reduction in K levels. The lowest K concentration was observed in April (0.03). Following April, the K concentration showed an increase, reaching 0.062 in July, but then decreased again to 0.027 in September.

In case of *Bambusa tulda* the potassium concentration ranged from 0.47% to 0.065%. Like other bamboo species, conc. of potassium was also higher in the initial litter mass (0.47%), characterized by an initial sharp decrease in potassium (K) concentration, followed by a slower rate of reduction in K levels. The lowest K concentration was observed in July (0.065%). Following July, the K concentration showed an increase, reaching 0.067% in august. Due to the rapid decomposition in *Bambusa tulda*, there was a negligible amount of remaining litter towards the end of the study (September) for the analysis of potassium concentration. Potassium concentration of *Dendrocalamus brandisii* ranged between 0.279% to 0.022%. Highest concentration of potassium was recorded in initial litter mass (0.279%). *Dendrocalamus brandisii* also showed initial sharp decrease in potassium concentration, followed by a slower rate of reduction in K levels. The lowest K concentration was observed in the last month (0.022). Similarly, in *Dendrocalamus asper* conc. of potassium was also highest in the initial litter mass (0.41%), characterized by an initial sharp decrease in potassium concentration, followed by a slower rate of reduction in K levels. The lowest K concentration was observed in the last month (0.012). In case of *Dendrocalamus longispathus* the potassium concentration ranged from 0.225% to 0.03% and like other species highest K concentration was also observed in initial litter mass(0.225%).During the first month of decomposition, there was a significant reduction in K concentration, followed by a slower decline, leading to the lowest recorded value in April (0.03), 210 days after incubation Throughout the decomposition process, the potassium concentration exhibited an almost similar trend in all the selected bamboo species litter.

4.2.4.3. Nutrient release pattern in decomposing litter

The data analysis indicated a significant variation in the percentage of nutrients remaining in the litter mass among different bamboo species over time. The percentages of nutrients retained in the litter mass of the selected bamboo species during various stages of decomposition are presented in a table13-15, while the percentages of nutrients released from the litter mass during different decomposition stages are depicted in a figure15-17.

4.2.4.3.1. Nitrogen

The percentage of nitrogen remaining in litter mass of selected bamboo species is presented in table 13 and the percentage release of nitrogen from decomposing litter is given in fig15. As a general trend, it was observed that all species exhibited a more rapid rate of nutrient release during the initial stages of decomposition. Initial release of nitrogen was observed highest in *Bambusa tulda* and lowest release was observed in *Bambusa balcooa*. For *Bambusa vulgaris*, after the initial 30 days of decomposition, approximately 41.02% of the original nitrogen content remained in the litter mass. This implies that about 58.98% of the nitrogen was released during the first month of decomposition, representing a relatively high rate of release compared to other periods. Additionally, there were two phases of nitrogen accumulation during February (150 days) and May (240 days), during which 0.18% and 4.29% of nitrogen was accumulated respectively. At the end of the study, roughly 4.79% of the nitrogen remained in the litter mass. In the case of *Bambusa balcooa*, about 48.40% of the original nitrogen content remained in the litter mass after the first 30 days of decomposition. This indicates that approximately 51.6% of the nitrogen was released during the initial 30 days, marking a relatively high release rate. Furthermore, there were three phases of nitrogen accumulation during March (180 days), May (240 days), and July (270 days), where 11.65%, 1.05%, and 3.45% of nitrogen were accumulated, respectively. At the end of the study, roughly 4.79% of the nitrogen remained in the litter mass.

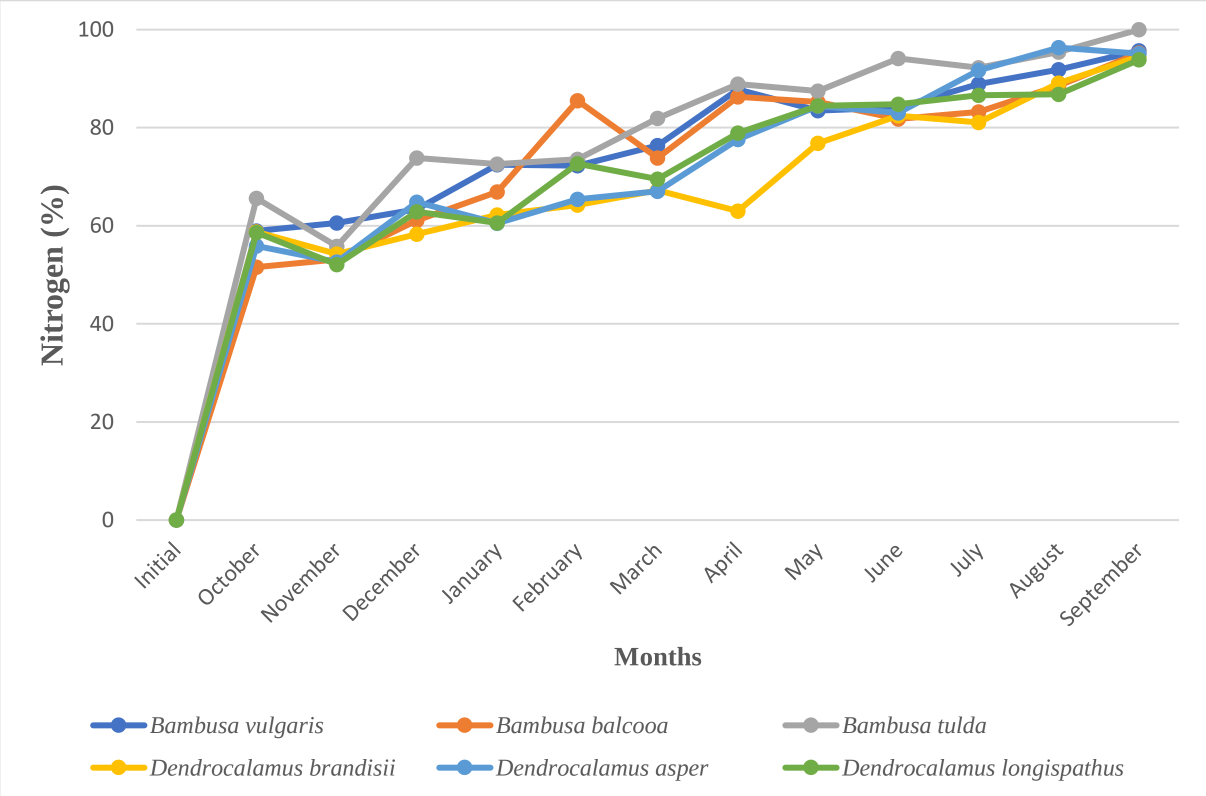


Fig.15. Nitrogen release (%) from the litter mass of bamboo species during decomposition at Vellanikkara, Thrissur

For *Bambusa tulda*, following the initial 30 days of decomposition, approximately 34.42% of the original nitrogen content remained in the litter mass. This signifies that roughly 65.58% of the nitrogen was released during the first month of decomposition, marking a relatively high release rate compared to other periods. Additionally, there were four phases of nitrogen accumulation during November (60 days), January (120 days), May (240 days), and July (270 days), during which 9.79%, 1.24%, 1.46%, and 1.9% of nitrogen were accumulated, respectively. At the end of the study in August, approximately 4.54% of the nitrogen remained in the litter mass. As for *Dendrocalamus brandisii*, after the initial 30 days of decomposition, around 41.23% of the original nitrogen content remained in the litter mass. This indicates that approximately 58.77% of the nitrogen was released during the first month of decomposition, also representing a relatively high release rate. There were three phases of nitrogen accumulation during November (60 days), April (210 days), and July (300 days), during which 4.52%, 4.21%, and 1.4% of nitrogen were accumulated, respectively. At the end of the study in August, roughly 5.47% of the original nitrogen concentration remained in the litter mass.

In case of *Dendrocalamus asper*, nitrogen remaining in the litter mass after one month of decomposition (30 days) was 44.10% of original mass which means that around 55.9% of nitrogen was released during the first 30 days of decomposition and it was quite high among the release of all periods. The litter also underwent through accumulation phase during November (60 days), January (120 days), June (270days) and September (360 day) in which 3.3 %, 4.3%,1.3% and 1.24% of nitrogen was accumulated respectively. The percentage of nitrogen remaining at end of study (September) was around 4.91% of original concentration. In case of *Dendrocalamus longispathus*, nitrogen remaining in the litter mass after one month of decomposition (30 days) was 41.40% of original mass which means that around 58.6% of nitrogen was released during the first 30 days of decomposition and it was quite high among the release of all periods. The litter also underwent through accumulation phase during November (60 days), January (120 days), and March (360 day) in which 6.47%, 2.33%, and 3.15% of nitrogen was accumulated respectively. The percentage of nitrogen remaining at end of study was around 6.16% of original concentration.

Table 13 Residual nitrogen (%) in the litter of bamboo species at different stages of decomposition at Vellanikkara, Thrissur

Months	Nitrogen (%) remaining in the litter mass						C.D. (0.05)
	Bambusa vulgaris	*Bambusa balcooa*	*Bambusa tulda*	*Dendrocalamus brandisii*	*Dendrocalamus asper*	*Dendrocalamus longispathus*	
Initial	100_{a}	100_{a}	100_{a}	100_{a}	100_{a}	100_{a}	ns
October	41.02_{b}^{BC}	48.40_{b}^{A}	34.42_{c}^{C}	41.23_{bc}^{BC}	44.10_{b}^{AB}	41.40_{bc}^{ABC}	7.05
November	39.41_{b}^{A}	46.86_{bc}^{A}	44.21_{b}^{A}	45.75_{b}^{A}	47.40_{b}^{A}	47.87_{b}^{A}	11.63
December	36.59_{bc}^{A}	38.89_{cd}^{A}	26.19_{d}^{B}	41.72_{bc}^{A}	35.15_{c}^{AB}	37.11_{bcd}^{A}	9.80
January	27.56_{cd}^{A}	33.08_{de}^{A}	27.43_{cd}^{A}	37.76_{bc}^{A}	39.45_{bc}^{A}	39.44_{bcd}^{A}	12.76
February	27.74_{cd}^{A}	14.49_{g}^{B}	26.41_{d}^{A}	35.73_{bc}^{A}	34.58_{c}^{A}	27.34_{def}^{A}	9.77
March	23.63_{de}^{AB}	26.14_{ef}^{AB}	18.07_{e}^{B}	32.79_{cd}^{A}	32.98_{c}^{A}	30.49_{cde}^{A}	9.89
April	12.23_{fg}^{C}	13.71_{g}^{C}	11.09_{efg}^{C}	37.00_{bc}^{A}	22.40_{d}^{B}	21.05_{efg}^{B}	5.39
May	16.52_{ef}^{AB}	14.76_{g}^{B}	12.55_{ef}^{B}	23.16_{de}^{A}	15.59_{de}^{B}	15.53_{fgh}^{B}	7.46
June	15.83_{ef}^{A}	18.21_{fg}^{A}	5.89_{fgh}^{B}	17.53_{ef}^{A}	16.97_{d}^{A}	15.22_{fgh}^{A}	5.67
July	11.07_{fg}^{BC}	16.75_{g}^{AB}	7.79_{fg}^{C}	18.93_{ef}^{A}	8.28_{ef}^{C}	13.38_{gh}^{ABC}	7.81
August	8.14_{fg}^{AB}	11.42_{gh}^{A}	4.54_{gh}^{B}	10.89_{fg}^{A}	3.67_{f}^{B}	13.17_{gh}^{A}	6.08
September	4.29_{g}^{A}	4.79_{h}^{A}	-	5.47_{g}^{A}	4.91_{f}^{A}	6.16_{h}^{A}	3.19
C.D. (0.05)	9.70	8.67	7.49	10.32	8.62	12.77	

With in row, means having same uppercase letters as superscript are homogeneous (significant at 1% level). Within column, means having same lowercase letters as subscripts are homogeneous (significant at 1% level)

4.2.4.3.2. Phosphorus

The percentage of phosphorus remaining in litter mass of selected bamboo species is presented in table 14 and the percentage release of phosphorus from decomposing litter is given in fig 16. In *Bambusa vulgaris*, the phosphorus remaining in the litter mass after the first month of decomposition was 83.24%, indicating that approximately 16.76% of phosphorus was released during the initial 30 days. Following this initial release, there were accumulation phases in November and December, during which 1.71% and 7.27% of phosphorus were accumulated in the decomposing litter. The highest release of phosphorus occurred in September (41.62%) at 360 days after incubation. At the end of the study, approximately 12.78% of the initial phosphorus concentration remained in the litter mass. In the case of *Bambusa balcooa*, roughly 125.32% of the phosphorus remained in the litter mass after the initial 30 days of decomposition, indicating an accumulation of about 25.32% of phosphorus during this period. Subsequently, there was a decline in phosphorus concentration in the litter up to May (240 days). The highest release of phosphorus was observed in December (36.86%) at 90 days after incubation. At the end of the study, approximately 19.92% of the initial phosphorus concentration remained in the litter mass.

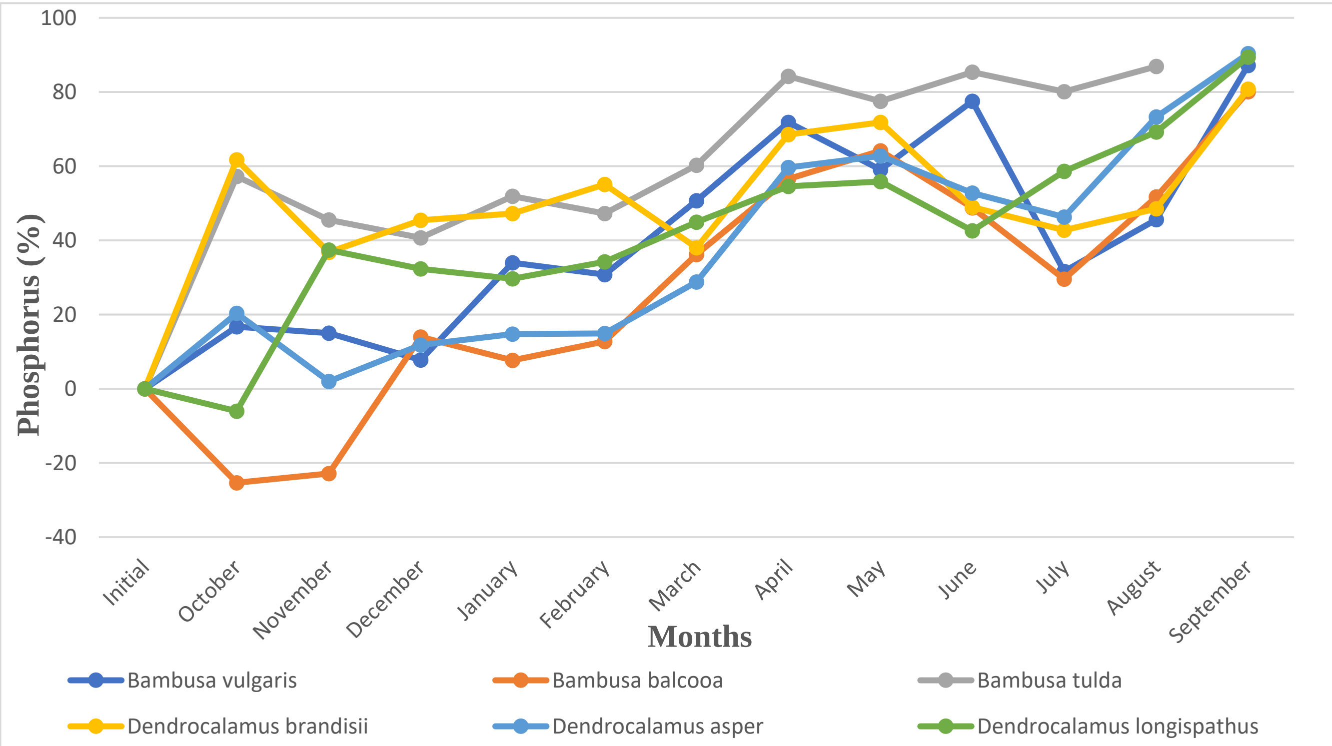


Fig.16. Phosphorus release (%) from the litter mass of bamboo species during decomposition at Vellanikkara, Thrissur

As for *Bambusa tulda*, the phosphorus content remaining in the litter mass after the first month of decomposition (30 days) was 42.70% of the original concentration. This signifies that around 57.53% of phosphorus was released during the initial 30 days, marking a relatively high release rate compared to other periods. After the initial release, there were accumulation phases in November and December, during which 11.73% and 4.88% of phosphorus were accumulated in the decomposing litter. At the end of the study (August) approximately 13.10% of the phosphorus remained in the litter mass.

As for *Dendrocalamus brandisii*, after the initial 30 days of decomposition, around 38.22% of the initial phosphorus content remained in the litter mass. This indicates that approximately 61.78% of the Phosphorus was released during the first month of decomposition, also representing a relatively high release rate. After initial release accumulation phase was observed during November (60 days), March (180 days), June (270 days) with accumulation 24.92%, 17.14% and 22.87% of P respectively. The percentage of P remaining at the end of the study was around 19.19% of initial concentration. In the case of *Dendrocalamus asper*, about 79.63% of the phosphorus remained in the litter mass after the first 30 days of decomposition. This indicates that approximately 20.37% of the phosphorus was released during the initial 30 days. After initial release accumulation phase was observed during November (60 days), June (270 days) and July (300 days) with accumulation 18.4%, 9.95% and 6.47% respectively. The highest release of p observed in April (30.95%) 210 days after the incubation. The percentage of P remaining at the end of the study was around 9,66% of initial concentration. In case of *Dendrocalamus longispathus* phosphorus remaining in the litter mass after one month of decomposition (30 days) was 106.03 % of original mass which means that around 6.03% of phosphorus was accumulated during the first 30 days of decomposition. After initial accumulation significant reduction in phosphorus content was observed in next subsequent November month around 43.47% of P release was observed during that period and it was quite high among the release of all periods. The percentage of P remaining at the end of the study was around 10.59% of initial concentration.

Table 14: Residual phosphorus (%) in the litter of bamboo species at different stages of decomposition at Vellanikkara, Thrissur

Months	**Phosphorus (%) remaining in the litter mass**						C.D (0.05)
	Bambusa vulgaris	*Bambusa balcooa*	*Bambusa tulda*	*Dendrocalamus brandisii*	*Dendrocalamus asper*	*Dendrocalamus longispathus*	
Initial	100_{a}	100_{bc}	100_{a}	100_{a}	100_{a}	100_{a}	
October	83.24_{ab}^{AB}	125.32_{a}^{A}	42.70_{bc}^{B}	38.22_{bc}^{B}	79.63_{ab}^{AB}	106.03_{a}^{A}	46.01
November	84.95_{ab}^{B}	122.88_{ab}^{A}	54.43_{bc}^{C}	63.14_{ab}^{C}	98.03_{a}^{B}	62.56_{bc}^{C}	15.96
December	92.22_{a}^{A}	86.02_{cde}^{AB}	59.31_{b}^{C}	54.54_{bc}^{C}	88.14_{ab}^{AB}	67.68_{bc}^{BC}	21.66
January	66.05_{bcd}^{BC}	92.32_{cd}^{A}	48.04_{bc}^{C}	52.71_{bc}^{C}	85.23_{ab}^{AB}	$70.31_{b\,A}^{BC}$	26.15
February	69.24_{bc}^{AB}	87.27_{cde}^{A}	52.72_{bc}^{BC}	44.86_{bc}^{C}	85.11_{ab}^{A}	65.72_{bc}^{B}	18.66
March	49.31_{de}^{BC}	63.78_{efg}^{AB}	39.69_{cd}^{C}	62.00_{b}^{AB}	71.23_{bc}^{A}	$55..05_{bcd}^{ABC}$	17.19
April	28.14_{fg}^{C}	43.41_{ghi}^{A}	15.77_{ef}^{D}	31.41_{bc}^{BC}	40.28_{de}^{AB}	45.44_{bcd}^{A}	11.84
May	40.96_{ef}^{A}	35.81_{hi}^{A}	22.46_{de}^{A}	28.13_{bc}^{A}	37.25_{de}^{A}	44.11_{bcd}^{A}	26.33
June	22.44_{fg}^{B}	51.18_{fgh}^{A}	14.63_{ef}^{B}	51.00_{bc}^{A}	47.20_{de}^{A}	57.38_{bcd}^{A}	18.62
July	68.36_{bcd}^{A}	70.43_{def}^{A}	19.87_{e}^{C}	57.22_{b}^{AB}	53.67_{cd}^{AB}	41.34_{cd}^{BC}	23.82
August	54.40_{cde}^{A}	48.26_{fgh}^{A}	13.10_{ef}^{B}	51.48_{bc}^{A}	26.68_{ef}^{AB}	30.78_{de}^{AB}	27.94
September	12.78_{g}^{A}	19.92_{i}^{A}	-	$19.19_{c\ AB}$	9.66_{f}^{AB}	10.59_{e}^{AB}	12.18
C.D(0.05)	19.57	23.56	17.25	37.63	24.01	27.98	

With in row, means having same uppercase letters as superscript are homogeneous (significant at 5% level). Within column, means having same lowercase letters as subscripts are homogeneous (significant at 5% level)

4.2.4.3.3. Potassium

In general, the initial month of decomposition in all selected bamboo species exhibited the highest potassium release rate, which subsequently decreased as the incubation period progressed. In *Bambusa vulgaris* the potassium remaining in the litter mass after the first month of decomposition was 28.27%, indicating that approximately 71.25% of potassium was released during the initial 30 days. Following this initial release, the accumulation phases was observed in November, during which 6.26% of potassium was accumulated in the decomposing litter. After which release of potassium occurred at a slower rate. The percentage of K remaining at the end of the study was around 1.39% of initial concentration. In the case of *Bambusa balcooa*, roughly 29.88% of the potassium remained in the litter mass after the initial 30 days of decomposition, indicating that about 70.12% of potassium was released during this period. Subsequently, there was an increase in K concentration during November or December indicating the accumulation of 2.55% and 2.81% of K in litter. The percentage of k remaining at the end of the study was around 1.42 % of initial concentration. In the case of *Bambusa tulda*, roughly 29.67% of the potassium remained in the litter mass after the initial 30 days of decomposition, indicating that about 70.33% of potassium was released during this period. Subsequently, there was an increase in K concentration during November, March, April and May indicating the accumulation of 8.36% ,2.6%, and 2.47% of K in litter. The percentage of k remaining at the end of the study was around 1.98 % of initial concentration. In the case *Dendrocalamus brandisii*, roughly 59.23% of the potassium remained in the litter mass after the initial 30 days of decomposition, indicating that about 40.77 % of potassium was released during this period. Subsequently, there was an increase in K concentration during March, May, June indicating the accumulation of 3.8% ,5.21%, and 0.17% of K in litter. The percentage of k remaining at the end of the study was around 1.22 % of initial concentration.

In the case *Dendrocalamus asper*, roughly 36.65 % of the potassium remained in the litter mass after the initial 30 days of decomposition, indicating that about 64.35% of potassium was released during this period. Subsequently, there was an increase in K concentration during January, April, May, and June indicating the accumulation of 3.89% ,1.88%,0.27% and 0.96% of K in litter. The percentage of k remaining at the end of the study was around 0.31 % of initial concentration.

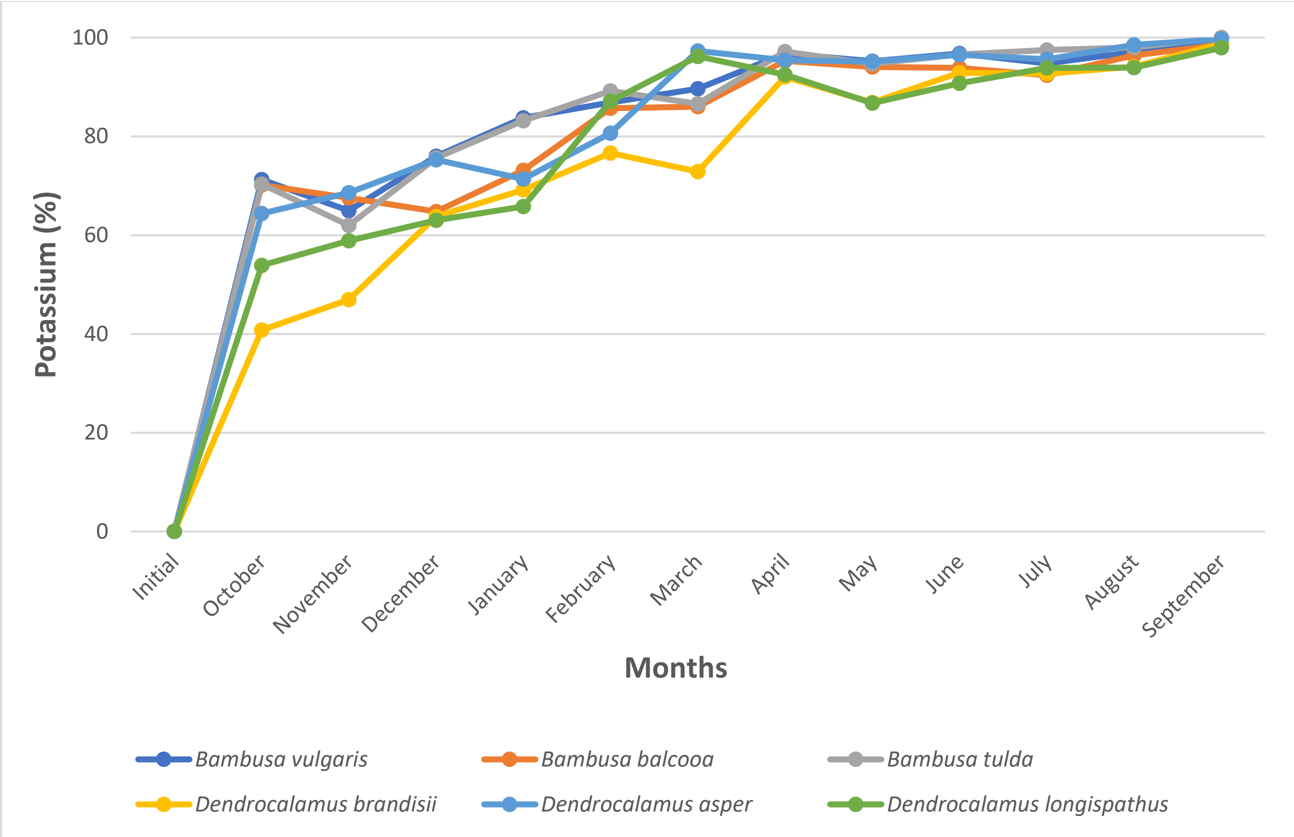


Fig.17. Potassium release (%) from the litter mass of bamboo species during decomposition at Vellanikkara, Thrissur

In the case *Dendrocalamus longispathus*, roughly 46.09 % of the potassium remained in the litter mass after the initial 30 days of decomposition, indicating that about 53.91% of potassium was released during this period. Subsequently, there was an increase in K concentration during April and may indicating the accumulation of 3.65 % and 5.81 % of K in litter. The percentage of K remaining at the end of the study was around 2.07 % of initial concentration.

Table 15: Residual potassium (%) in the litter of bamboo species at different stages of decomposition at Vellanikkara, Thrissur

Months	**Potassium (%) remaining in the litter mass of**						C.D (0.05)
	Bambusa vulgaris	*Bambusa balcooa*	*Bambusa tulda*	*Dendrocalamus brandisii*	*Dendrocalamus asper*	*Dendrocalamus longispathus*	
Initial	100_{a}	100_{a}	100_{a}	100_{a}	100_{a}	100_{a}	
October	28.75_{bc}^{C}	29.88_{bc}^{C}	29.67_{c}^{C}	59.23_{b}^{A}	35.65_{b}^{C}	46.09_{b}^{B}	9.11
November	35.01_{b}^{BC}	32.43_{bc}^{C}	38.03_{b}^{BC}	53.04_{b}^{A}	31.43_{bc}^{C}	41.14_{b}^{B}	7.34
December	24.01_{c}^{B}	35.24_{b}^{AB}	24.36_{c}^{B}	36.18_{c}^{A}	24.74_{bc}^{B}	36.98_{b}^{A}	11.33
January	16.27_{d}^{B}	26.85_{bcd}^{AB}	16.84_{d}^{B}	30.83_{cd}^{A}	28.63_{bc}^{A}	34.19_{b}^{A}	11.74
February	13.15_{d}^{B}	14.32_{cde}^{AB}	10.80_{de}^{B}	23.35_{d}^{A}	19.35_{c}^{AB}	12.88_{c}^{B}	9.17
March	10.33_{de}^{C}	14.00_{cde}^{B}	13.40_{d}^{B}	27.15_{d}^{A}	2.69_{d}^{D}	3.82_{c}^{D}	2.32
April	3.20_{f}^{C}	4.73_{e}^{BC}	2.85_{f}^{C}	7.95_{ef}^{A}	4.57_{d}^{C}	7.47_{c}^{AB}	2.78
May	4.76_{ef}^{B}	5.96_{e}^{B}	5.32_{ef}^{B}	13.16_{e}^{A}	4.84_{d}^{B}	13.28_{c}^{A}	3.33
June	3.21_{f}^{C}	6.12_{e}^{B}	3.41_{f}^{C}	7.13_{ef}^{B}	3.45_{d}^{C}	9.24_{c}^{A}	2.00
July	5.20_{ef}^{ABC}	7.61_{de}^{A}	2.50_{f}^{C}	7.30_{ef}^{AB}	4.41_{d}^{BC}	6.14_{c}^{AB}	3.00
August	2.88_{f}^{B}	3.59_{e}^{AB}	1.98_{f}^{B}	5.85_{ef}^{A}	1.45_{d}^{B}	6.06_{c}^{A}	2.55
September	1.39_{f}^{AB}	1.42_{e}^{AB}	-	1.22_{f}^{B}	0.31_{d}^{C}	2.07_{c}^{A}	0.84
C.D(0.05)	6.52	19.90	7.00	8.04	13.70	14.57	

With in row, means having same uppercase letters as superscript are homogeneous (significant at 5% level). Within column, means having same lowercase letters as subscripts are homogeneous (significant at 1% level)

4.3. Physico chemical properties of soil under selected bamboo species

4.3.1. Soil physical properties

4.3.1.1. Bulk density

Data regarding the soil bulk density of selected bamboo species at various depths during two sampling period is presented in Table 16. Data observed here represent an increasing trend from top layer(0-20cm) to bottom layer(80-100cm) in both sampling periods.

Table 16: Soil bulk density (g cm^{-3}) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

	Bulk density (g cm^{-3})					
	Species	**Depth (cm)**				
		0-20	21-40	41-60	61-80	81-100
Initial (November,2022)	*Bambusa vulgaris*	1.03^{cd}	1.07^{bc}	1.12^{bc}	1.17^{c}	1.19
	Bambusa balcooa	1.00^{d}	1.04^{c}	1.13^{bc}	1.20^{c}	1.40
	Bambusa tulda	1.06^{bcd}	1.08^{bc}	1.09^{c}	1.19^{c}	1.27
	Dendrocalamus brandisii	1.03^{cd}	1.08^{bc}	1.14^{bc}	1.23^{bc}	1.27
	Dendrocalamus asper	1.12^{a}	1.17^{a}	1.22^{ab}	1.26^{bc}	1.34
	Dendrocalamus longispathus	1.07^{bc}	1.14^{ab}	1.26^{a}	1.30^{ab}	1.36
	Open	1.14^{a}	1.18^{a}	1.29^{a}	1.38^{a}	1.41
	P value	<0.01	0.01	<0.01	<0.01	NS
	C.D (0.05)	0.07	0.08	0.10	0.10	
Final (September,2023)	*Bambusa vulgaris*	1.03^{b}	1.06^{b}	1.14^{cd}	1.20^{c}	1.20^{c}
	Bambusa balcooa	1.02^{b}	1.07^{b}	1.21^{bc}	1.18^{c}	1.35^{ab}
	Bambusa tulda	1.03^{b}	1.07^{b}	1.12^{d}	1.21^{c}	1.27^{bc}
	Dendrocalamus brandisii	1.02^{b}	1.07^{b}	1.14^{cd}	1.24^{bc}	1.29^{bc}
	Dendrocalamus asper	1.03^{b}	1.14^{ab}	1.20^{bcd}	1.26^{bc}	1.35^{ab}
	Dendrocalamus longispathus	1.01^{b}	1.11^{ab}	1.24^{ab}	1.31^{b}	1.36^{ab}
	Open	1.15^{a}	1.19^{a}	1.30^{a}	1.40^{a}	1.44^{a}
	P value	0.13	0.04	<0.01	<0.01	<0.01
	C.D(0.05)	0.10	0.09	0.09	0.08	0.10

Within a column, means having same letters as superscripts are homogeneous

Tables 16 showed a significant difference in bulk density between selected bamboo species across different depths. During both sampling period highest bulk density in topsoil layer (0-20cm) was observed in open (bamboo less) area having value of 1.14 g cm^{-3} and 1.15 g cm^{-3} respectively. At the depth of 0-20 cm lowest bulk density was observed in *Bambusa balcooa* (1.02gcm^{-3}) during initial sampling and *Dendrocalamus brandisii* (1.02g cm^{-3}) during final sampling. At the depth of 21-40cm bulk density showed a significant difference between selected bamboo species during both sampling periods. Similar trend was observed at the depth of 41-60, 61-80, 81-100cm.Generally, when compared with soil depths highest bulk density was observed in lower depths (80-100cm) in all selected bamboo species during both sampling seasons. Exploration of data showed except in open (bamboo less) a slight decrease in bulk density was observed in final sampling when compared with values taken during initial sampling.

4.3.1.2. Particle density

The data in Table 17 provides information on soil particle density for selected bamboo species at various depths during two separate sampling periods. The data reveals a consistent increasing trend from the top layer (0-20cm) to the bottom layer (80-100cm) during both sampling periods. The table indicates that there is no significant variation in particle density among the selected bamboo species across different depths. In both sampling periods, the highest particle density in the topsoil layer (0-20cm) was observed in the open (bamboo-less) area, with values of 2.59 g cm^{-3} (initial) and 2.58 g cm^{-3} (final), respectively. At a depth of 0-20 cm, the lowest bulk density was observed in *Dendrocalamus longispathus* (2.32 g cm^{-3}) during both the initial sampling (2.32 g cm^{-3}) and final sampling (2.31 g cm-3). At a depth of 21-40cm, particle density showed a non-significant difference between selected bamboo species during both sampling periods, with the highest value observed in the open (bamboo less) area and *Bambusa vulgaris*, i.e., 2.60 g cm^{-3} during the initial sampling and again in the open (bamboo less) area, i.e., 2.59 g cm^{-3} during the final sampling. The lowest values of particle density at a depth of 20-41cm were observed in *Dendrocalamus asper* (2.43 g cm^{-3}) during the initial sampling and in *Bambusa tulda* and *Dendrocalamus asper*, i.e., 2.45 g cm-3 during the final sampling. This trend continued in a similar fashion at the 41-60cm, 61-80cm, and 81-100cm depths.

Table 17: Soil particle density (g cm^{-3}) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

	Particle density (g cm^{-3})					
	Species	**Depth (cm)**				
		0-20	21-40	41-60	61-80	81-100
Initial (November,2022)	*Bambusa vulgaris*	2.58	2.60	2.64	2.56	2.65
	Bambusa balcooa	2.54	2.54	2.52	2.55	2.64
	Bambusa tulda	2.49	2.46	2.56	2.58	2.61
	Dendrocalamus brandisii	2.55	2.59	2.60	2.64	2.64
	Dendrocalamus asper	2.40	2.43	2.45	2.46	2.50
	Dendrocalamus longispathus	2.32	2.58	2.59	2.63	2.65
	Open	2.59	2.60	2.62	2.63	2.66
	P value	NS	NS	NS	NS	NS
Final (September,2023)	*Bambusa vulgaris*	2.54	2.58	2.60	2.62	2.67
	Bambusa balcooa	2.53	2.53	2.54	2.55	2.64
	Bambusa tulda	2.46	2.45	2.52	2.55	2.61
	Dendrocalamus brandisii	2.51	2.54	2.58	2.60	2.62
	Dendrocalamus asper	2.38	2.45	2.46	2.47	2.52
	Dendrocalamus longispathus	2.31	2.61	2.62	2.63	2.65
	Open	2.58	2.59	2.59	2.61	2.66
	P value	NS	NS	NS	NS	NS

Within a column, means having same letters as superscripts are homogeneous

4.3.1.3. Soil Porosity

The data in Table 18 provides information on soil porosity for six bamboo species at various depths during two separate sampling periods. The information in the table depicts a consistent trend of decreasing soil porosity from the upper layer (0-20cm) to the lower layer (80-100cm) in both sampling periods. The table indicates that there is no significant variation in soil porosity among the selected bamboo species across different depths. At the depth of 0-20cm high porosity was observed in all selected bamboo species and the highest value was observed under the *Bambusa balcooa* during both initial (60.34%) and final sampling (59.69%).

Table 18: Soil porosity (%) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

	Porosity (%)					
	Species	**Depth (cm)**				
		0-20	21-40	41-60	61-80	81-100
Initial (November,2022)	*Bambusa vulgaris*	59.90	58.75	57.36	54.50	54.87
	Bambusa balcooa	60.34	59.05	54.66	52.40	46.68
	Bambusa tulda	57.39	56.11	57.40	53.66	51.22
	Dendrocalamus brandisii	59.34	58.04	56.12	53.26	51.58
	Dendrocalamus asper	53.37	51.31	50.17	48.67	46.18
	Dendrocalamus longispathus	53.76	55.95	52.12	49.63	48.72
	Open	53.26	54.72	50.75	47.67	46.95
	P value	NS	NS	NS	NS	NS
Final (September,2023)	*Bambusa vulgaris*	59.40	58.79	56.36	53.88	55.05
	Bambusa balcooa	59.69	57.86	52.67	53.02	48.87
	Bambusa tulda	58.17	56.38	55.42	52.74	51.19
	Dendrocalamus brandisii	59.04	57.53	55.69	52.23	50.63
	Dendrocalamus asper	56.74	53.16	51.10	48.85	46.55
	Dendrocalamus longispathus	56.20	57.14	51.90	50.10	48.29
	Open (Bamboo less)	53.28	53.93	49.66	46.48	45.79
	P value	NS	NS	NS	NS	NS

Within a column, means having same letters as superscripts are homogeneous

The lowest value during initial sampling was observed for open (53.26%) followed by *Dendrocalamus asper* (53.37%) and again lowest porosity was observed under open (53.28%) followed by *Dendrocalamus longispathus* (56.20%) during final sampling period. Similar non-significant variation in porosity was observed across different selected species at varying depths, including 21-40cm, 41-60cm, 61-80cm, and 81-100cm.

4.3.1.4. Soil moisture

The data in Table 19 provides information on soil moisture under six bamboo species at various depths during two separate sampling periods. The data from the table reveals a consistent increasing trend of soil moisture as one move from the top layer (0-20cm) to the bottom layer (80-100cm) in both sampling periods.

Table 19: Soil moisture content (%) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

	Moisture content (%)					
	Species	**Depth (cm)**				
		0-20	21-40	41-60	61-80	81-100
Initial (November,2022)	*Bambusa vulgaris*	7.78^{c}	10.96^{abc}	10.41	10.32	12.63
	Bambusa balcooa	9.03^{bc}	12.19^{ab}	13.10	13.62	12.54
	Bambusa tulda	10.99^{a}	13.21^{a}	14.47	15.68	15.87
	Dendrocalamus brandisii	7.78^{c}	9.71^{c}	10.02	10.91	11.90
	Dendrocalamus asper	7.89^{c}	10.65^{bc}	11.06	12.39	12.90
	Dendrocalamus longispathus	9.48^{ab}	11.19^{abc}	11.65	11.98	14.80
	Open	8.27^{bc}	8.98^{c}	10.55	12.24	12.88
	P value	<0.01	0.02	NS	NS	NS
	C.D(0.05)	1.58	2.36			
Final (September,2023)	*Bambusa vulgaris*	14.22^{ab}	14.36^{b}	13.14^{bc}	15.14^{bcd}	16.98^{ab}
	Bambusa balcooa	13.73^{ab}	14.63^{b}	14.83^{ab}	13.46^{de}	15.71^{bc}
	Bambusa tulda	16.16^{a}	17.00^{a}	17.24^{a}	17.44^{a}	18.49^{a}
	Dendrocalamus brandisii	14.03^{ab}	14.27^{b}	15.44^{ab}	17.27^{ab}	18.00^{a}
	Dendrocalamus asper	13.25^{abc}	14.15^{bc}	14.42^{b}	15.89^{abc}	16.02^{bc}
	Dendrocalamus longispathus	11.14^{bc}	12.42^{bc}	14.22^{bc}	14.55^{cd}	15.39^{bc}
	Open	10.00^{c}	11.98^{c}	11.72^{c}	11.82^{e}	14.44^{c}
	P value	0.02	<0.01	0.01	<0.01	<0.01
	C.D(0.05)	3.32	2.28	2.61	2.18	1.96

Within a column, means having same letters as superscripts are homogeneous

Furthermore, the table also suggests that there is a statistically significant differences in soil moisture among the different selected bamboo species at the depth of 0-20, 21-40cm during both sampling period. At a depth of 0-20cm, all selected bamboo species exhibited low soil moisture content compared to the other depths. The lowest moisture value in this layer, during the initial sampling period, was recorded for *Bambusa vulgaris* (7.78%), which was statistically at par with *Dendrocalamus asper* (7.89%). In the final sampling period, the lowest moisture content at 0-20cm was found in open areas (10.00%), followed by *Dendrocalamus longispathus* (11.14%). The highest values of soil moisture in 0-20cm depth were found in *Bambusa tulda* (10.99%) during the initial sampling period. In the final sampling period, the moisture content at 0-20cm was again found highest in *Bambusa tulda* (16.16%). At the depth of 21-40cm soil moisture showed a significant difference between selected bamboo species during both sampling periods. In contrast, at the depths of 41-60cm, 61-80cm, and 81-100cm, soil moisture did not exhibit statistically significant differences among the selected bamboo species during the initial sampling. However, during the final sampling period, there was a significant difference in soil moisture levels among the species at these greater depths.

4.3.2. Soil chemical properties

4.3.2.1. Soil pH

The data in Table 20 provides information on soil pH of selected six bamboo species at various depths during two separate sampling periods. The lowest pH value at the depth of 0-20cm during the initial sampling period, was recorded for *Bambusa tulda* (5.23), which was statistically at par with all other bamboo species except for open (5.63) which however recorded the highest value during initial sampling. In the final sampling period, the lowest pH values were observed under *Bambusa balcooa* (5.34) followed by *Dendrocalamus longispathus* (5.39), while highest value was again observed under open (5.63). At depth of 20-41 pH variation among different species was observed to statistically unsignificant during initial sampling while it was interesting to note that pH values at 21-40cm among different species was observed to be statistically significant during final sampling. At depth of 41-60cm Ph showed significant difference between selected bamboo species during both initial sampling and final sampling period. Similar trend of pH was also observed across different selected species at remaining depths, including 41-60cm, 61-80cm, and 81-100cm during both seasons.

Table 20: Soil pH under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

	pH					
	Species	**Depth (cm)**				
		0-20	21-40	41-60	61-80	81-100
Initial (November,2022)	*Bambusa vulgaris*	5.33^{b}	5.25	5.23^{b}	5.32^{b}	5.35^{b}
	Bambusa balcooa	5.25^{b}	5.36	5.25^{b}	5.33^{b}	5.36^{b}
	Bambusa tulda	5.23^{b}	5.10	5.34^{b}	5.36^{b}	5.22^{b}
	Dendrocalamus brandisii	5.27^{b}	5.27^{b}	5.36^{b}	5.39^{b}	5.27^{b}
	Dendrocalamus asper	5.26^{b}	5.29	5.30^{b}	5.39^{b}	5.19^{b}
	Dendrocalamus longispathus	5.29^{b}	5.35	5.22^{b}	5.27^{b}	5.36^{b}
	Open	5.63^{a}	5.70	5.77^{a}	5.81^{a}	5.84^{a}
	P value	<0.01	NS	<0.01	<0.01	<0.01
	C.D(0.05)	0.12		0.27	0.12	0.22
Final (September,2023)	*Bambusa vulgaris*	5.41^{cde}	5.45^{abc}	5.37^{bc}	5.45^{bc}	5.58^{bc}
	Bambusa balcooa	5.34^{e}	5.28^{c}	5.35^{c}	5.40^{bc}	5.46^{cd}
	Bambusa tulda	5.50^{bc}	5.59^{ab}	5.56^{ab}	5.63^{ab}	5.61^{bc}
	Dendrocalamus brandisii	5.56^{ab}	5.58^{ab}	5.63^{a}	5.66^{ab}	5.65^{b}
	Dendrocalamus asper	5.44^{cd}	5.45^{abc}	5.39^{bc}	5.40^{bc}	5.40^{d}
	Dendrocalamus longispathus	5.39^{de}	5.41^{bc}	5.27^{c}	5.29^{c}	5.34^{d}
	Open	5.58^{a}	5.61^{a}	5.67^{a}	5.79^{a}	5.83^{a}
	P value	<0.01	0.01	<0.01	0.01	<0.01
	C.D(0.05)	0.08	0.18	0.20	0.27	0.17

Within a column, means having same letters as superscripts are homogeneous

Generally, there was a modest relation between pH value with increasing soil depth, except in open (bamboo-less) areas where the soil pH showed an increasing trend with depth during both sampling periods Also, it was interesting to note that value of pH was increased in final sampling season compared to initial sampling values.

4.3.2.2. Soil EC

The data in Table 21 provides information on soil EC among six bamboo species at various depths during two separate sampling periods. Exploration of EC data reveals that there were no significant differences among the selected bamboo species at various depths during both the initial and final sampling periods. The only exceptions were observed at depths of 21-40cm, 41-60cm, and 61-80cm during final sampling, where significant variations among the selected bamboo species were evident.

Table 21: Soil EC (dS m^{-1}) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

	EC (dS m^{-1})					
	Species	**Depth (cm)**				
		0-20	21-40	41-60	61-80	81-100
Initial (November,2022)	*Bambusa vulgaris*	0.050	0.020	0.036	0.020	0.023
	Bambusa balcooa	0.053	0.043	0.023	0.023	0.023
	Bambusa tulda	0.070	0.053	0.030	0.023	0.030
	Dendrocalamus brandisii	0.040	0.026	0.023	0.023	0.033
	Dendrocalamus asper	0.050	0.030	0.030	0.020	0.046
	Dendrocalamus longispathus	0.043	0.026	0.023	0.017	0.020
	Open	0.053	0.033	0.023	0.020	0.020
	P value	NS	NS	NS	NS	NS
	C.D(0.05)	0.043	0.041	0.012	0.012	0.034
Final (September,2023)	*Bambusa vulgaris*	0.063	0.047^{c}	0.043^{b}	0.037^{b}	0.023
	Bambusa balcooa	0.143	0.083^{b}	0.043^{b}	0.033^{bc}	0.020
	Bambusa tulda	0.053	0.040^{c}	0.030^{c}	0.020^{c}	0.027
	Dendrocalamus brandisii	0.083	0.047^{c}	0.030^{c}	0.026^{bc}	0.040
	Dendrocalamus asper	0.103	0.053^{c}	0.033^{bc}	0.033^{bc}	0.047
	Dendrocalamus longispathus	0.070	0.033^{c}	0.043^{b}	0.030^{bc}	0.037
	Open	0.100	0.123^{a}	0.100^{a}	0.093^{a}	0.053
	P value	NS	<0.01	<0.01	<0.01	NS
	C.D(0.05)	0.090	0.023	0.012	0.016	0.027

Within a column, means having same letters as superscripts are homogeneous

At the depth of 0-20 cm highest EC values was recorded under *Bambusa tulda* (0.070 dS m^{-1}) and lowest under *Dendrocalamus brandisii* (0.040 dS m^{-1}) during the initial sampling while during the final sampling highest EC value were recorded under *Bambusa balcooa* (0.143 dS m^{-1}) and lowest under *Bambusa tulda* (0.053 dS m^{-1}). At the depth of 21-40 cm the highest EC was observed under *Bambusa tulda* (0.053) and lowest under *Bambusa vulgaris* (0.020 dS m^{-1}) during the initial sampling while during the final sampling highest EC value were recorded under Open (0.123 dS m^{-1}) and lowest under *Dendrocalamus longispathus* (0.033 dS m^{-1}). Similar trend of EC was also observed across different selected species at remaining depths, including 41-60cm, 61-80cm, and 81-100cm. The data revealed that as soil depth increased, the EC of the soil generally decreased. However, there was a slight increase in EC values at the lower depth (81-100cm) compared to the upper depth (61-80cm), but in case of open areas, there was a consistent decrease in EC as soil depth increased. Yet another observation is that there was increase in soil EC value during final sampling when compared to initial sampling values.

4.3.2.3. Soil organic carbon

The data in Table 22 provides information on soil organic carbon of selected six bamboo species at various depths during two separate sampling periods. Exploration of data reveals that there were significant differences among the selected bamboo species at various depths during both the initial and final sampling periods. It was observed that there was a steady decline in soil carbon content as the soil depth increased. Additionally, it was observed that bamboo plots exhibited higher concentrations of organic carbon compared to the adjacent open (bamboo-less) areas. For example, at the depth of 0-20 cm the highest organic carbon content was observed under *Bambusa balcooa* (1.78%) and lowest under *open area* (1.08%) during the initial sampling while during the final sampling again highest organic carbon value were recorded under *Bambusa balcooa* (1.79%) and lowest open (1.07%). At a depth of 21-40cm also, there was significant difference in soil organic carbon between different bamboo species with the highest organic carbon content was again observed under *Bambusa balcooa* (1.30%) and lowest under open area (0.62%) during the initial sampling while during the final sampling highest organic carbon value were recorded under *Dendrocalamus longispathus* (1.17%) and lowest under open (0.92%). At the depth of 41-60cm again there was significant difference in soil organic carbon between different bamboo species with the highest organic carbon content was observed under *Dendrocalamus longispathus* (0.97%) which was statistically at par with *Bambusa balcooa* (0.95%) and lowest under open area (0.52%) during the initial sampling while during the final sampling highest organic carbon value were recorded under

Dendrocalamus longispathus (0.97%) and lowest under *Bambusa tulda* (0.54%). Similar trend was also observed at the depth of 61-80cm and 81-100cm.

Table 22: Soil organic carbon (%) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

	Organic Carbon (%)					
	Species	Depth (cm)				
		0-20	21-40	41-60	61-80	81-100
Initial (November,2022)	*Bambusa vulgaris*	1.49^{ab}	1.17^{ab}	0.88^{ab}	0.76^{ab}	0.47^{ab}
	Bambusa balcooa	1.78^{a}	1.30^{a}	0.95^{a}	0.76^{ab}	0.50^{ab}
	Bambusa tulda	1.40^{bc}	1.02^{ab}	0.72^{bc}	0.63^{bc}	0.53^{ab}
	Dendrocalamus brandisii	1.26^{bc}	0.83^{bc}	0.80^{ab}	0.61^{bc}	0.65^{a}
	Dendrocalamus asper	1.30^{bc}	0.96^{abc}	0.53^{cd}	0.61^{bc}	049^{ab}
	Dendrocalamus longispathus	1.50^{ab}	1.03^{b}	0.97^{a}	0.85^{a}	0.68^{a}
	Open	1.08^{c}	0.62^{c}	0.52^{d}	0.43^{c}	0.32^{b}
	P value	0.02	0.02	<0.01	0.01	0.05
	C.D(0.05)	0.35	0.35	0.19	0.20	0.22
Final (September,2023)	*Bambusa vulgaris*	1.55^{ab}	0.97^{b}	0.79^{ab}	0.56^{b}	0.35^{b}
	Bambusa balcooa	1.79^{a}	0.78^{c}	0.65^{bc}	0.39^{c}	0.32^{b}
	Bambusa tulda	1.43^{abc}	0.93^{b}	0.54^{c}	0.58^{b}	0.47^{b}
	Dendrocalamus brandisii	1.27^{bc}	0.87^{bc}	0.68^{abc}	0.55^{bc}	0.45^{b}
	Dendrocalamus asper	1.38^{bc}	0.98^{b}	0.50^{c}	0.48^{bc}	0.35^{b}
	Dendrocalamus longispathus	1.51^{ab}	1.17^{ab}	0.90^{a}	0.77^{a}	0.72^{a}
	Open	1.07^{c}	0.92^{b}	0.78^{ab}	0.58^{b}	0.38^{b}
	P value	0.02	<0.01	0.01	0.01	<0.01
	C.D(0.05)	0.37	0.13	0.22	0.17	0.15

Within a column, means having same letters as superscripts are homogeneous

Further analysis of the data uncovered that the decrease in organic carbon content with increasing soil depth under bamboo plots occurred at a slower rate compared to the open area. Additionally, it was intriguing to observe that the organic carbon content in the upper soil layer increased in the final sampling season in comparison to the values recorded during the initial sampling.

4.3.2.4. Available Nitrogen

The data in Table 23 provides information on soil available nitrogen among six bamboo species at various depths during two separate sampling periods. Exploration of data reveals that there were significant differences among the six bamboo species at various depths during both the initial and final sampling periods. It was observed that bamboo plots exhibited higher concentrations of available nitrogen compared to the adjacent open (bamboo-less) areas with an exception in *Dendrocalamus brandisii* in which soil available nitrogen was lower than open plot. At a depth of 0-20cm, significant difference in soil available nitrogen was observed between different bamboo species with the highest available nitrogen was observed under *Dendrocalamus longispathus*(200.70 Kg ha^{-1}) which was statistically at par with *Dendrocalamus asper*(198.61 Kg ha^{-1}) and *Bambusa tulda* (196.52 Kg ha^{-1}) and lowest under *Dendrocalamus brandisii* (121.26 Kg ha^{-1}) during the initial sampling while during the final sampling highest available nitrogen value were recorded under *Dendrocalamus longispathus* (194.43 Kg ha^{-1}) which was statistically at par with *Dendrocalamus asper* (183.98 Kg ha^{-1}), *Bambusa tulda* (183.98 Kg ha^{-1}) , *Bambusa balcooa* (179.80 Kg ha^{-1}) and *Bambusa vulgaris* (169.34 Kg ha^{-1}) and lowest under *Dendrocalamus brandisii* (117.08 Kg ha^{-1}). At a depth of 21-40cm also, there was significant difference in soil available nitrogen between different bamboo species with the highest available nitrogen content was again observed under *Dendrocalamus longispathus* (196.52 Kg ha^{-1}) and lowest under *Dendrocalamus brandisii* (117.08 Kg ha^{-1}) during the initial sampling while during the final sampling highest available nitrogen value were recorded under *Dendrocalamus longispathus* (181.89 Kg ha^{-1}) and lowest under *Dendrocalamus brandisii* (133.80 Kg ha^{-1}). Again, similar trend was observed at the depth of 41-60, 61-80cm and 81-100cm.

Generally, there was a modest relation between available nitrogen value with increasing soil depth, typically, under all bamboo species, the available nitrogen decreased as the depth increased, but this trend was observed only up to a depth of 21-40cm. Subsequently, a general increase in available nitrogen was noted at the depth of 41-60cm compared to the shallower depth and subsequently, the available nitrogen levels began to decrease once more at the lower depths. Additionally, it was intriguing to observe that the available nitrogen content in the upper soil layer decreased in the final sampling season in comparison to the values recorded during the initial sampling.

Table 23: Available Nitrogen (Kg ha^{-1}) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

	Available Nitrogen (Kg ha^{-1})					
	Species	**Depth (cm)**				
		0-20	21-40	41-60	61-80	81-100
Initial (November,2022)	*Bambusa vulgaris*	171.43^{bc}	167.25^{bc}	183.98^{a}	158.89^{bc}	150.53^{abc}
	Bambusa balcooa	192.34^{ab}	179.80^{ab}	200.70^{a}	196.52^{a}	163.07^{ab}
	Bambusa tulda	196.52^{a}	183.64^{ab}	181.89^{a}	179.80^{abc}	175.62^{a}
	Dendrocalamus brandisii	121.26^{d}	117.08^{d}	137.98^{b}	121.26^{d}	117.07^{c}
	Dendrocalamus asper	198.61^{a}	154.71^{c}	154.71^{b}	146.35^{cd}	133.80^{bc}
	Dendrocalamus longispathus	200.70^{a}	196.52^{a}	200.70^{a}	192.34^{ab}	175.62^{a}
	Open	162.57^{c}	165.05^{bc}	158.76^{b}	153.82^{cd}	146.58^{abc}
	P value	<0.01	<0.01	<0.01	<0.01	0.05
	C.D(0.05)	24.34	18.91	22.41	35.29	39.91
Final (September,2023)	*Bambusa vulgaris*	169.34^{ab}	154.71^{bcd}	160.98^{ab}	152.62^{ab}	148.44^{abc}
	Bambusa balcooa	179.80^{ab}	177.04^{ab}	140.07^{bc}	137.98^{bc}	125.44^{cd}
	Bambusa tulda	183.98^{ab}	167.25^{abc}	175.61^{a}	171.43^{a}	163.07^{a}
	Dendrocalamus brandisii	117.08^{c}	133.80^{d}	131.71^{c}	120.42^{c}	116.24^{d}
	Dendrocalamus asper	183.98^{ab}	152.62^{cd}	150.53^{bc}	144.26^{bc}	129.20^{bcd}
	Dendrocalamus longispathus	194.43^{a}	181.89^{a}	173.52^{a}	160.98^{ab}	158.04^{ab}
	Open	152.69^{bc}	169.60^{abc}	157.99^{ab}	151.68^{ab}	146.80^{abcd}
	P value	0.01	0.01	<0.01	0.01	0.05
	C.D(0.05)	37.94	24.33	22.08	24.74	32.15

Within a column, means having same letters as superscripts are homogeneous

4.3.2.5. Available Phosphorus

The data in Table 24 provides information on soil available phosphorus of selected six bamboo species at various depths during two separate sampling periods. Exploration of data reveals that there were significant differences among the selected bamboo species at various depths during both the initial and final sampling periods. In general, there is a significant difference in available phosphorus concentration between selected bamboo species across all the depths.

Table 24: Available phosphorus (Kg ha^{-1}) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

	Available Phosphorus (Kg ha^{-1})					
	Species	**Depth (cm)**				
		0-20	21-40	41-60	61-80	81-100
Initial (November,2022)	*Bambusa vulgaris*	3.62^{c}	5.23^{b}	2.80^{ab}	1.94^{bc}	2.13^{bc}
	Bambusa balcooa	4.67^{abc}	3.56^{cd}	2.76^{ab}	2.24^{b}	3.77^{b}
	Bambusa tulda	4.70^{abc}	3.17^{cd}	3.06^{a}	2.35^{b}	3.36^{bc}
	Dendrocalamus brandisii	5.30^{ab}	2.99^{cd}	2.16^{c}	2.50^{b}	2.84^{bc}
	Dendrocalamus asper	3.84^{bc}	3.96^{bc}	2.54^{abc}	2.31^{b}	2.99^{bc}
	Dendrocalamus longispathus	5.90^{a}	7.70^{a}	2.39^{bc}	6.86^{a}	6.68^{a}
	Open	4.21bc	2.04d	2.92^{ab}	1.16^{c}	1.32^{c}
	P value	0.05	<0.01	0.04	<0.01	<0.01
	C.D(0.05)	1.46	1.61	0.55	0.82	2.14
Final (September,2023)	*Bambusa vulgaris*	3.51^{d}	4.78^{ab}	2.61^{bc}	2.35^{bc}	4.22^{a}
	Bambusa balcooa	4.63^{abc}	3.99^{bc}	3.02^{ab}	3.92^{a}	2.16^{b}
	Bambusa tulda	4.14^{bcd}	2.50^{d}	2.13^{c}	2.02^{c}	2.31^{b}
	Dendrocalamus brandisii	5.19^{a}	3.02^{cd}	1.94^{cd}	3.17^{ab}	2.46^{b}
	Dendrocalamus asper	3.81^{cd}	2.46^{d}	3.43^{a}	1.68^{cd}	2.46^{b}
	Dendrocalamus longispathus	5.00^{ab}	5.19^{a}	3.47^{a}	1.87^{cd}	4.37^{a}
	Open	2.25^{e}	1.21^{e}	1.16^{d}	1.07^{d}	2.05^{b}
	P value	<0.01	<0.01	<0.01	<0.01	<0.01
	C.D(0.05)	0.93	1.16	0.81	0.96	0.79

Within a column, means having same letters as superscripts are homogeneous

At a depth of 0-20cm, significant difference in soil available P was observed among different bamboo species with the highest available P was observed under *Dendrocalamus longispathus* (5.90 Kg ha^{-1}) which was statistically at par with *Dendrocalamus brandisii* (5.30 Kg ha^{-1}), *Bambusa tulda* (4.70 Kg ha^{-1}) and *Bambusa balcooa* (4.67 Kg ha^{-1}) and lowest under

Bambusa vulgaris (3.62 Kg ha^{-1}) during the initial sampling while during the final sampling highest available P value were recorded under *Dendrocalamus brandisii* (5.19 Kg ha^{-1}) which was statistically at par with *Dendrocalamus longispathus*(5.00 Kg ha^{-1}), and *Bambusa balcooa* (4.63 Kg ha^{-1}) and lowest under open area (2.25 Kg ha^{-1}). At a depth of 21-40cm also, there was significant difference in soil available P between different bamboo species with the highest available P content was again observed under *Dendrocalamus longispathus* (7.70 Kg ha^{-1}) and lowest under open(2.04 Kg ha^{-1}) during the initial sampling while during the final sampling highest available P value were recorded under *Dendrocalamus longispathus* (5.19 Kg ha^{-1})and lowest under open (1.21 Kg ha^{-1}) Again, similar trend was observed at the depth of 41-60, 61-80cm and 81-100cm.

Generally, there was a modest relation between available P value with increasing soil depth as soil available P under all bamboo species did not follow a particular trend with increasing soil depth. Additionally, it was intriguing to observe that the available P content in the upper soil layer decreased in the final sampling season in comparison to the values recorded during the initial sampling.

4.3.2.6. Available Potassium

The data in Table 25 provides information on soil available potassium of selected six bamboo species at various depths during two separate sampling periods. Exploration of data reveals that there were significant differences among the selected bamboo species at various depths during both the initial and final sampling periods. In general, there is a significant difference in available potassium concentration between selected bamboo species across all the depths. Among six bamboo species, the highest concentration of available potassium was consistently observed in the uppermost layer(0-20cm) of the soil during both sampling periods. However, there was an exception with *Bambusa vulgaris*, where high K concentration was found at a depth of 41-60cm. At a depth of 0-20cm, significant difference in soil available K was observed between different bamboo species with the highest available K was observed under *Dendrocalamus longispathus*(193.01 Kg ha^{-1}) which was statistically at par with *Dendrocalamus asper* (167.63 Kg ha^{-1}), *Bambusa tulda* (166.88 Kg ha^{-1}) and open (162.96 Kg ha^{-1}) and lowest under *Bambusa vulgaris* (101.92 Kg ha^{-1}) during the initial sampling while during the final sampling highest available K value were recorded under *Dendrocalamus longispathus* (271.78 Kg ha^{-1}) and lowest under open area (174.46 Kg ha^{-1}). At a depth of 21-40cm also, there was a significant difference in soil available K between different bamboo species with the highest available K content was again observed under *Dendrocalamus longispathus* (155.31 Kg ha^{-1}) which was statistically at par with *Dendrocalamus asper*

(152.32) and lowest under *Bambusa balcooa* (122.80 Kg ha^{-1}) which was statistically at par with open (124.20 Kg ha^{-1}) and *Bambusa vulgaris*(124.69 Kg ha^{-1}) during the initial sampling while during the final sampling highest available K value were recorded under *Dendrocalamus longispathus* (159.71 Kg ha^{-1})and lowest under open (98.72 Kg ha^{-1}) Again, similar trend was observed at the depth of 41-60, 61-80cm and 81-100cm.

Table 25: Available potassium (Kg ha^{-1}) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

	Available Potassium (Kg ha^{-1})					
	Species	**Depth (cm)**				
		0-20	21-40	41-60	61-80	81-100
Initial (November,2022)	*Bambusa vulgaris*	101.92^{c}	124.69^{b}	126.56^{b}	102.67^{cd}	96.69^{cd}
	Bambusa balcooa	145.23^{b}	122.08^{b}	124.32^{b}	117.97^{bc}	113.49^{bc}
	Bambusa tulda	166.88^{ab}	144.48^{ab}	151.95^{a}	154.93^{a}	152.69^{a}
	Dendrocalamus brandisii	140.37^{b}	125.81^{b}	126.56^{b}	122.45^{bc}	124.69^{b}
	Dendrocalamus asper	167.63^{ab}	152.32^{a}	151.95^{a}	136.64^{ab}	150.82^{a}
	Dendrocalamus longispathus	193.01^{a}	155.31^{a}	132.53^{ab}	132.90^{b}	126.93^{b}
	Open	162.96^{ab}	124.20^{b}	97.13^{c}	88.71^{d}	94.21^{d}
	P value	<0.01	0.03	<0.01	<0.01	<0.01
	C.D(0.05)	38.35	25.02	22.26	19.97	18.82
Final (September,2023)	*Bambusa vulgaris*	191.52^{cd}	110.85^{de}	100.42^{cd}	98.56^{cd}	75.04^{d}
	Bambusa balcooa	209.98^{bcd}	122.22^{cd}	119.13^{bc}	82.88^{de}	105.28^{c}
	Bambusa tulda	211.31^{bcd}	146.56^{ab}	114.61^{bcd}	110.88^{bc}	123.94^{ab}
	Dendrocalamus brandisii	245.61^{abc}	140.00^{bc}	122.45^{b}	129.55^{a}	115.73^{bc}
	Dendrocalamus asper	258.69^{ab}	150.08^{ab}	145.22^{a}	120.21^{ab}	138.13^{a}
	Dendrocalamus longispathus	271.78^{a}	159.17^{a}	101.17^{cd}	88.11^{de}	101.54^{c}
	Open	174.46^{d}	98.72^{e}	95.02^{d}	80.21^{e}	78.64^{d}
	P value	0.02	<0.01	<0.01	<0.01	<0.01
	C.D(0.05)	58.55	19.14	19.76	18.17	17.86

Within a column, means having same letters as superscripts are homogeneous

The data in table revealed that, there was a steady decline in soil available potassium as the soil depth increased. Additionally, it was intriguing to observe that the available K content in the upper soil layer increased in the final sampling season in comparison to the values recorded during the initial sampling.

4.3.2.7. Calcium

The data in Table 26 provides information on soil calcium content among six bamboo species at various depths during two separate sampling periods. Exploration of data reveals that there were significant differences among the selected bamboo species at various depths during both the initial and final sampling periods.

In all selected bamboo species, the highest concentration of calcium content was consistently observed in the lowermost layer(80-100cm) of the soil during both sampling periods. At a depth of 0-20cm, significant difference in calcium content was observed between different bamboo species with the highest calcium was observed under *Dendrocalamus asper* (324.92 mg kg^{-1}) and lowest under *Bambusa vulgaris* (152.29 mg kg^{-1}) which was statistically at par with open (155.30 mg kg^{-1}) during the initial sampling while during the final sampling highest calcium value were recorded under *Dendrocalamus asper* (310.54 mg kg^{-1}) and lowest under open area (115.80 mg kg^{-1}). Also, similar trend was observed at the depth of 21-40, 41-60, 61-80 and 81-100cm. It was quite interesting to see that, calcium content under all bamboo species increased with increasing soil depth during both sampling seasons. Additionally, it was also observed that the calcium content in the upper soil layer decreased in the final sampling season in comparison to the values recorded during the initial sampling. However, there was an exception in the case of *Bambusa tulda* and *Dendrocalamus brandisii*, where an increase in calcium values was observed.

Table 26: Soil calcium content (mg kg^{-1}) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

	Calcium (mg kg^{-1})					
	Species	**Depth (cm)**				
		0-20	21-40	41-60	61-80	81-100
Initial (November,2022)	*Bambusa vulgaris*	152.29^{c}	152.45^{c}	169.27^{c}	207.92^{c}	243.00^{c}
	Bambusa balcooa	191.98^{bc}	191.21^{bc}	228.00^{bc}	216.54^{c}	203.47^{c}
	Bambusa tulda	234.77^{b}	249.50^{ab}	278.10^{ab}	322.60^{b}	380.00^{b}
	Dendrocalamus brandisii	234.92^{b}	258.90^{ab}	321.87^{a}	390.31^{a}	417.65^{ab}
	Dendrocalamus asper	324.92^{a}	293.15^{a}	318.02^{a}	297.58^{b}	451.25^{a}
	Dendrocalamus longispathus	238.02^{b}	243.44^{ab}	241.52^{b}	257.70^{bc}	271.98^{c}
	Open	155.30^{c}	231.67^{ab}	235.22^{bc}	259.51^{bc}	261.07^{c}
	P value	<0.01	0.02	<0.01	<0.01	<0.01
	C.D(0.05)	73.00	72.52	67.82	67.08	69.36
Final (September,2023)	*Bambusa vulgaris*	148.23^{cd}	154.42^{bc}	178.21^{c}	195.72^{c}	255.42
	Bambusa balcooa	186.25^{bcd}	152.31^{c}	182.85^{c}	237.83^{bc}	262.46
	Bambusa tulda	249.12^{ab}	233.37^{a}	255.46^{a}	298.06^{a}	302.15
	Dendrocalamus brandisii	271.02^{ab}	228.31^{a}	193.87^{bc}	219.75^{bc}	252.56
	Dendrocalamus asper	310.54^{a}	236.44^{a}	235.12^{ab}	239.19^{bc}	270.83
	Dendrocalamus longispathus	212.04^{bc}	215.12^{ab}	239.25^{ab}	239.02^{bc}	241.94
	Open	115.80^{d}	218.08^{a}	218.67^{abc}	251.24^{ab}	230.45
	P value	<0.01	0.03	0.01	0.03	NS
	C.D(0.05)	86.02	61.70	45.52	54.13	

Within a column, means having same letters as superscripts are homogeneous

4.3.2.8. Magnesium

The data in Table 27 provides information on soil magnesium content under six bamboo species at various depths during two separate sampling periods. Exploration of data reveals that there were significant differences among the selected bamboo species at various depths during both the initial and final sampling periods.

Table 27: Soil magnesium content (mg kg^{-1}) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

	Magnesium (mg kg^{-1})					
	Species	**Depth (cm)**				
		0-20	21-40	41-60	61-80	81-100
Initial (November,2022)	*Bambusa vulgaris*	80.85^{cd}	79.79^{c}	81.10^{c}	87.19^{c}	109.97^{b}
	Bambusa balcooa	97.44^{bc}	102.58^{b}	134.46^{b}	119.69^{bc}	120.46^{b}
	Bambusa tulda	151.29^{a}	159.96^{a}	185.85^{a}	212.06^{a}	239.64^{a}
	Dendrocalamus brandisii	85.54^{bcd}	99.00^{bc}	113.42^{bc}	129.62^{b}	138.12^{b}
	Dendrocalamus asper	101.02^{b}	85.27^{bc}	118.62^{bc}	107.10^{bc}	139.72^{b}
	Dendrocalamus longispathus	73.75^{d}	92.08^{bc}	92.42^{c}	81.31^{c}	92.15^{b}
	Open	67.08^{d}	98.94^{bc}	83.10^{c}	102.23^{bc}	101.10^{b}
	P value	<0.01	<0.01	<0.01	<0.01	<0.01
	C.D(0.05)	18.26	21.39	40.88	42.05	59.61
Final (September,2023)	*Bambusa vulgaris*	75.04^{cd}	80.37^{bc}	83.12^{c}	87.10^{c}	101.04^{bcd}
	Bambusa balcooa	95.75^{bcd}	87.83^{bc}	99.67^{bc}	108.44^{b}	114.83^{bc}
	Bambusa tulda	158.54^{a}	151.65^{a}	159.33^{a}	167.25^{a}	170.04^{a}
	Dendrocalamus brandisii	110.44^{b}	104.65^{a}	112.35^{b}	125.83^{b}	132.44^{b}
	Dendrocalamus asper	100.85^{bc}	92.62^{bc}	91.52^{bc}	85.50^{c}	94.21^{cd}
	Dendrocalamus longispathus	70.96^{cd}	71.67^{c}	76.71^{c}	73.04^{c}	71.96^{d}
	Open	64.62^{d}	100.94^{bc}	88.62^{bc}	109.04^{b}	96.21^{bcd}
	P value	<0.01	<0.01	<0.01	<0.01	<0.01
	C.D(0.05)	34.68	32.79	25.38	21.22	37.13

Within a column, means having same letters as superscripts are homogeneous

In all selected bamboo species, the highest concentration of magnesium content was consistently observed in the lowermost layer(80-100cm) of the soil during both sampling periods. At a depth of 0-20cm, significant difference in magnesium content was observed between different bamboo species with the highest magnesium was observed under *Bambusa tulda* (151.29 mg kg^{-1}) and lowest under open (67.08 mg kg^{-1}) during the initial sampling while during the final sampling highest magnesium content were recorded under *Bambusa tulda*

(158.54 mg kg^{-1}) *and* lowest under open area (64.62 mg kg^{-1}). Also, similar trend was observed at the depth of 21-40 41-60, 61-80 and 81-100cm. It was quite interesting to see that, magnesium content under all bamboo species increased with increasing soil depth during both sampling seasons. Additionally, it was also observed that the magnesium content in the upper soil layer decreased in the final sampling season in comparison to the values recorded during the initial sampling. However, there was an exception in the case of *Bambusa tulda* and *Dendrocalamus brandisii*, where an increase in magnesium values was observed.

4.3.2.9. Sulphur

The data in Table 28 provides information on soil sulphur content under six bamboo species at various depths during two separate sampling periods. Exploration of data reveals that there were significant differences among the selected bamboo species at various depths during both the initial and final sampling periods. In all selected bamboo species, the highest concentration of sulphur content was consistently observed in the uppermost layer(0-20cm) of the soil during both sampling periods.

At a depth of 0-20cm, significant difference in sulphur content was observed between different bamboo species with the highest sulphur was observed under *Bambusa tulda* (4.95 mg kg^{-1}) and lowest under *Bambusa vulgaris* (2.20 mg kg^{-1}) which was statistically at par with *Dendrocalamus brandisii*(2.39 mg kg^{-1}) during the initial sampling while during the final sampling highest sulphur value were recorded under *Bambusa tulda* (4.15 mg kg^{-1}) was statistically at par with *Dendrocalamus asper* (3.92 mg kg^{-1}) *and* lowest under *Dendrocalamus brandisii*(2.10 mg kg^{-1}). Also, similar trend was observed at the depth of 21-40 41-60, 61-80 and 81-100cm. It was observed that there was a steady decline in sulphur content as the soil depth increased. Additionally, it was also observed that the sulphur content in the upper soil layer decreased in the final sampling season in comparison to the values recorded during the initial sampling.

Table 28: Soil sulphur content (mg kg^{-1}) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

	Sulphur (mg kg^{-1})					
	Species	**Depth (cm)**				
		0-20	21-40	41-60	61-80	81-100
Initial (November,2022)	*Bambusa vulgaris*	2.20^{c}	1.32^{c}	1.20^{d}	1.07^{e}	0.82^{cd}
	Bambusa balcooa	4.30^{ab}	3.71^{a}	2.16^{bc}	2.11^{cd}	0.47^{d}
	Bambusa tulda	4.95^{a}	3.20^{ab}	2.73^{b}	3.30^{a}	0.59^{cd}
	Dendrocalamus brandisii	2.39^{c}	2.64^{abc}	2.52^{b}	2.50^{bc}	1.99^{ab}
	Dendrocalamus asper	4.03^{abc}	3.59^{ab}	3.90^{a}	2.83^{ab}	2.95^{a}
	Dendrocalamus longispathus	2.95^{bc}	1.89^{bc}	2.89^{b}	1.70^{de}	1.51^{bc}
	Open	3.57^{abc}	1.45^{c}	1.30^{cd}	1.29^{e}	0.98^{cd}
	P value	0.05	0.03	<0.01	<0.01	<0.01
	C.D(0.05)	1.84	1.73	0.94	0.63	0.94
Final (September,2023)	*Bambusa vulgaris*	2.15^{cd}	2.34^{d}	1.81^{b}	1.63^{bc}	1.82^{abc}
	Bambusa balcooa	3.76^{a}	3.09^{bc}	2.88^{a}	2.50^{a}	0.97^{c}
	Bambusa tulda	4.15^{a}	3.76^{a}	2.38^{ab}	2.45^{a}	1.19^{bc}
	Dendrocalamus brandisii	2.10^{d}	2.77^{cd}	2.90^{a}	2.60^{a}	2.12^{ab}
	Dendrocalamus asper	3.92^{a}	3.63^{ab}	3.13^{a}	2.30^{ab}	2.26^{ab}
	Dendrocalamus longispathus	2.92^{bc}	3.61^{ab}	2.86^{a}	2.42^{a}	2.49^{a}
	Open	3.39^{ab}	2.42^{d}	2.42^{ab}	1.54^{c}	1.57^{abc}
	P value	<0.01	<0.01	0.04	0.02	0.08
	C.D(0.05)	0.79	0.66	0.78	0.69	1.10

Within a column, means having same letters as superscripts are homogeneous

4.3.3. Soil biological properties

4.3.3.1. Total microbial count

The data in Table 29-31 provides information on total bacterial population under six bamboo species in the top layer of the soil during two separate sampling periods. Exploration of data reveals that the bacterial population were significantly different among the selected bamboo species during both the initial and final sampling periods. The highest bacterial population was observed under *Dendrocalamus longispathus* (7.02 cfu g^{-1}) which was statistically at par with *Bambusa vulgaris* (6.82 cfu g^{-1}) and lowest under open (6.40 cfu g^{-1}) which was statistically at par with *Bambusa balcooa* (6.42 cfu g^{-1}) during initial sampling while during final sampling highest population was observed under *Dendrocalamus brandisii* (7.42 cfu g^{-1}) and lowest under open (6.80).It was observed that bacterial population under bamboo species were higher compared with adjacent open area during both sampling period. Additionally, it was also observed that the bacterial population increased in the final sampling season in comparison to the values recorded during the initial sampling.

Table 29: Total bacterial population (cfu g^{-1}) under selected bamboo species during two sampling periods at Vellanikkara, Thrissur

Total bacterial population (cfu g^{-1}) × 10 ^{6} dilution		
Species	**Initial count (November,2022)**	**Final count (September,2023)**
Bambusa vulgaris	7.00× 10 ^{6} (6.82^{ab})	9.50× 10 ^{6}(6.97^{c})
Bambusa balcooa	2.67× 10 ^{6} (6.42^{d})	13.50× 10 ^{6} (7.13^{b})
Bambusa tulda	5.50× 10 ^{6} (6.71^{bc})	7.00× 10 ^{6} (6.83^{d})
Dendrocalamus brandisii	5.50× 10 ^{6} (6.74^{bc})	26.50× 10 ^{6} (7.42^{a})
Dendrocalamus asper	3.17× 10 ^{6} (6.48^{cd})	17.00× 10 ^{6} (7.23^{b})
Dendrocalamus longispathus	11.00× 10 ^{6} (7.02^{a})	16.33× 10 ^{6} (7.21^{b})
Open	2.50× 10 ^{6} (6.40^{d})	6.50× 10 ^{6} (6.80^{d})
P value	<0.01	<0.01
C.D(0.05)	0.26	0.14

*Parentheses contain log transformed values
Within a column, means having same letters as superscripts are homogeneous

The data in Table 30 provides information on total actinomycetes population in selected six bamboo species in the top layer of the soil during two separate sampling periods. Exploration of data reveals that the actinomycetes population were significantly different among the selected bamboo species during both the initial and final sampling periods.

The highest actinomycetes population was observed under *Bambusa vulgaris* (4.81 cfu g^{-1}) which was statistically at par with *Bambusa tulda* (4.80 cfu g^{-1}), *Dendrocalamus asper (4.74* cfu g^{-1}*), Dendrocalamus brandisii (4.69* cfu g^{-1}*), Dendrocalamus longispathus* (4.69 cfu g^{-1}) and lowest under open (4.16 cfu g^{-1}) during initial sampling while during final sampling highest population was observed under *Bambusa tulda* (4.95 cfu g^{-1}) which was statistically at par with *Bambusa vulgaris* (4.90 cfu g^{-1}) and lowest under open (4.48 cfu g^{-1}). It was observed that actinomycetes population under bamboo species were higher compared with adjacent open area during both sampling period. Additionally, it was also observed that the actinomycetes population increased in the final sampling season in comparison to the values recorded during the initial sampling.

Table 30: Total actinomycetes population (cfu g^{-1}) under selected bamboo species during two sampling periods at Vellanikkara, Thrissur

Total actinomycetes population (cfu g^{-1}) ×10 ^{4} dilution		
Species	**Initial count (November,2022)**	**Final count (September,2023)**
Bambusa vulgaris	6.50× 10 ^{4} (4.81^a)	8.00× 10 ^{4} (4.90^a)
Bambusa balcooa	4.00× 10 ^{4} (4.59^b)	4.50× 10 ^{4} (4.65^c)
Bambusa tulda	6.50× 10 ^{4} (4.80^a)	9.00× 10 ^{4} (4.95^a)
Dendrocalamus brandisii	5.00× 10 ^{4} (4.69^{ab})	5.50× 10 ^{4} (4.74^b)
Dendrocalamus asper	5.50× 10 ^{4} (4.74^{ab})	5.67× 10 ^{4} (4.75^b)
Dendrocalamus longispathus	5.00× 10 ^{4} (4.69^{ab})	5.67× 10 ^{4} (4.75^b)
Open	1.50× 10 ^{4} (4.16^c)	3.00× 10 ^{4} (4.48^d)
P value	<0.01	<0.01
C.D(0.05)	0.17	0.08

*Parentheses contain log transformed values
Within a column, means having same letters as superscripts are homogeneous

The data in Table 31 provides information on total fungal population in selected six bamboo species in the top layer of the soil during two separate sampling periods. Exploration of data reveals that the fungal population were significantly different among the selected bamboo species during both the initial and final sampling periods.

The highest fungal population was observed under *Dendrocalamus longispathus* (4.84 cfu g^{-1}) which was statistically at par with *Bambusa tulda* (4.80 cfu g^{-1}), *Bambusa balcooa* (4.69 cfu g^{-1}), *Dendrocalamus brandisii* (4.67 cfu g^{-1}) , *Dendrocalamus asper* (4.64 cfu g^{-1}) and lowest under *Bambusa vulgaris* (4.46 cfu g^{-1}) during initial sampling while during final sampling highest population was observed under *Dendrocalamus longispathus (*5.10 cfu g^{-1}) which was statistically at par with *Bambusa tulda*(4.99 cfu g^{-1}) and lowest under open (4.73 cfu g^{-1}). It was observed that fungal population under bamboo species were higher compared with adjacent open area during both sampling period. However, there was an exception in the case of *Bambusa vulgaris*, where the fungal population was observed to be the lowest during the initial sampling. Additionally, it was also observed that the fungal population increased in the final sampling season in comparison to the values recorded during the initial sampling.

Table 31: Total fungal population (cfu g^{-1}) under selected bamboo species during two sampling periods at Vellanikkara, Thrissur

Total fungal population (cfu g^{-1}) ×10 ^{4} dilution		
Species	**Initial count (November,2022)**	**Final count (September,2023)**
Bambusa vulgaris	3.00× 10 ^{4} (4.46^b)	7.5× 10 ^{4} (4.87^{bc})
Bambusa balcooa	5.00× 10 ^{4} (4.69^a)	5.67 × 10 ^{4} (4.75^{cd})
Bambusa tulda	6.50× 10 ^{4} (4.80^a)	10× 10 ^{4} (4.99^{ab})
Dendrocalamus brandisii	5.00× 10 ^{4} (4.67^{ab})	8.5× 10 ^{4} (4.93^b)
Dendrocalamus asper	4.50× 10 ^{4} (4.64^{ab})	6.17× 10 ^{4} (4.79^{cd})
Dendrocalamus longispathus	7.00× 10 ^{4} (4.84^a)	12.5× 10 ^{4} (5.10^a)
Open	4.33× 10 ^{4} (4.63^{ab})	5.5× 10 ^{4} (4.73^d)
P value	0.03	<0.01
C.D(0.05)	0.21	0.13

*Parentheses contain log transformed values
Within a column, means having same letters as superscripts are homogeneous

4.3.3.2. Dehydrogenase activity

The data in Table 32 provides information on dehydrogenase activity in selected six bamboo species in the top layer of the soil during two separate sampling periods. Exploration of data reveals that the dehydrogenase activity was significantly different among the selected bamboo species during both the initial and final sampling periods.

The highest dehydrogenase activity was observed under *Bambusa tulda* (8.40 µg TPF g^{-1} 24 hr^{-1}) which was statistically at par with *Bambusa balcooa* (5.52 µg TPF g^{-1} 24 hr^{-1}), and *Dendrocalamus asper* (5.24 µg TPF g^{-1} 24 hr^{-1}) and lowest under open (1.87 µg TPF g^{-1} 24 hr^{-1}) which was statistically at par with *Bambusa vulgaris* (1.90 µg TPF g^{-1} 24 hr^{-1}) during initial sampling while during final sampling highest dehydrogenase activity was observed under *Bambusa tulda* (9.01 µg TPF g^{-1} 24 hr^{-1}) and lowest under open (0.76 µg TPF g^{-1} 24 hr^{-1}). It was observed that dehydrogenase activity under bamboo species were higher compared with adjacent open area during both sampling period. Additionally, it was also observed that the dehydrogenase activity increased in the final sampling season in comparison to the values recorded during the initial sampling.

Table 32: Dehydrogenase activity (µg TPF g^{-1} 24 hr^{-1}) under selected bamboo species during two sampling periods at Vellanikkara, Thrissur

Dehydrogenase activity (µg TPF g^{-1} 24 hr^{-1})		
Species	**Initial (November,2022)**	**Final (September,2023)**
Bambusa vulgaris	1.90^{b}	2.78^{d}
Bambusa balcooa	5.52^{ab}	5.56^{bc}
Bambusa tulda	8.40^{a}	9.01^{a}
Dendrocalamus brandisii	4.15^{b}	6.37^{b}
Dendrocalamus asper	5.24^{ab}	5.94^{b}
Dendrocalamus longispathus	3.68^{b}	3.89^{cd}
Open	1.87^{b}	0.76^{e}
P value	0.05	<0.01
C.D(0.05)	4.13	1.78

Within a column, means having same letters as superscripts are homogeneous

Discussion

5. DISCUSSION

The findings of the study entitled "Litter dynamics and soil changes under six-year-old bamboo stands" are discussed with reference to related research works and available literature in this chapter.

5.1. Growth performance of selected bamboo species

Growth refers to the irreversible changes in the size of a cell, organ, or whole plant. It encompasses various aspects such as an augmentation in length or height and stem girth (Pandey *et al.,* 2017). Bamboo is amongst the fastest growing plants on the earth, but the rate of growth can differ significantly among its various species, and this variation is influenced by factors such as climate, soil conditions, and other environmental variables (Amlani *et al.,* 2017).

In the current study, clump height was found to be significantly varying in different bamboo species (Fig.18). Among the species *D. brandisii* had shown highest clump height followed by *D. longispathus and D. asper* respectively during all observational periods. Amani *et al.* (2022) also observed similar trend in the clump height of six different bamboo species in Kerala condition, where *D. longispathus* (12.25m) and *Dendrocalamus asper* (11.83m) outperformed the other bamboo species. Similar trends were observed by Getahun *et al.* (2023) where *D. asper* (8.02m) recorded highest culm height compared to other bamboo species. Nevertheless, the clump height of the same bamboo species can exhibit variations due to soil and environmental conditions. For example, reports from Tapi, Gujarat, indicated a clump height of 17.73m for *B. vulgaris*, whereas in the current study, the corresponding measurement for *B. vulgaris* was 12.83m. However, certain species like *B. tulda* displayed consistency in clump height 10.45m (present observation), in contrast to the value reported by Amlani *et al.,* 2017 which was 10.09m which is comparable to the present results.

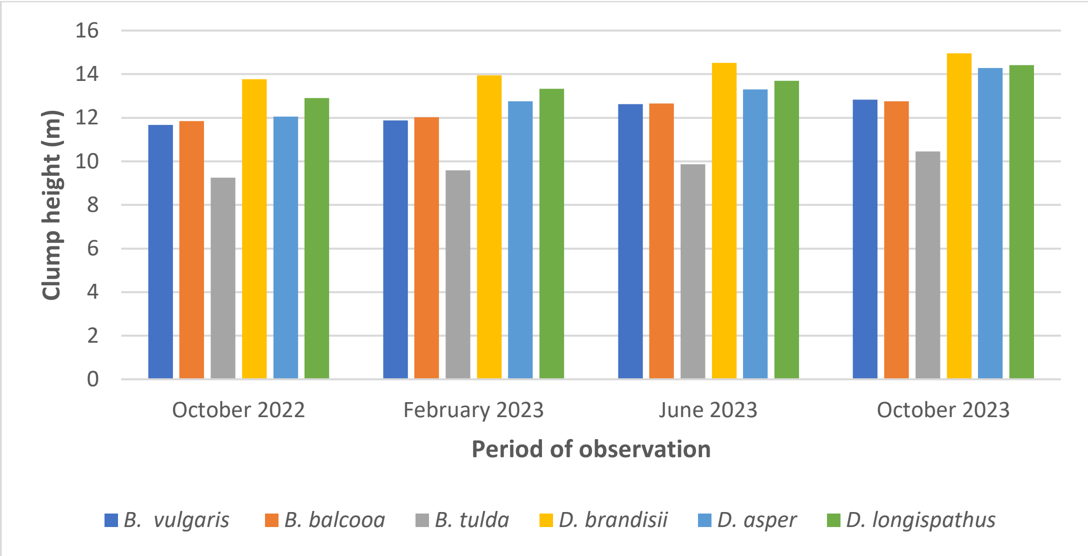


Fig.18. Variation in clump height of six bamboo species at seventh year of growth (October 2022- October 2023) at Vellanikkara, Thrissur

In the current study culm girth was found to be significantly influenced by different bamboo species under all observational period (Fig.19). Among the six bamboo species, the highest culm girth was recorded for *B. vulgaris* followed by *D. brandisii*, and *D. asper* respectively during all observational periods. However, the findings appear to contradict the results reported by Amani *et al.,* 2022, where *D. brandisii* (2year old) had displayed greater culm girth compared to *B. vulgaris* (2year old). This suggests the possibility that the rate of culm girth growth for a species may vary with its age. Similar results were also reported from the Gujrat where highest culm diameter was also found for *B. vulgaris* (7.54cm), indicating species influence on culm girth (Amlani *et al.,* 2017).

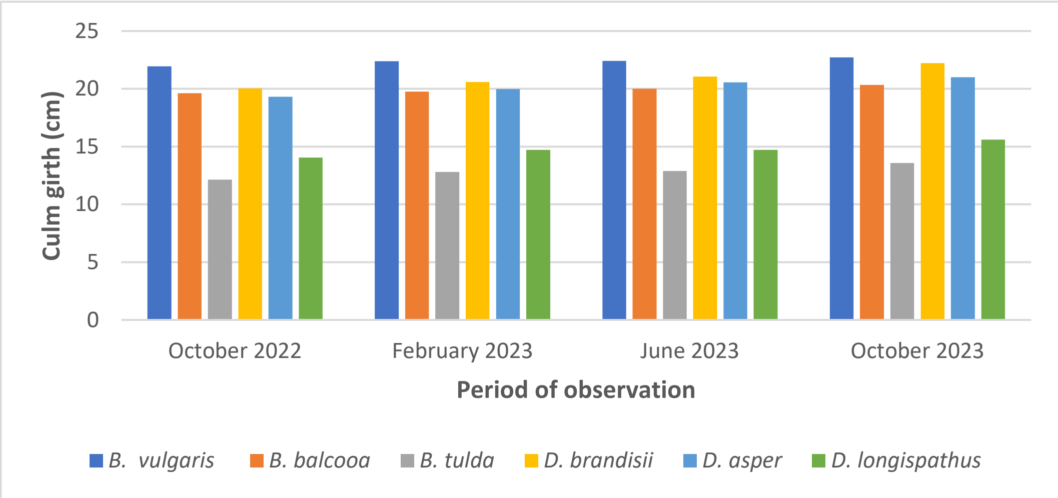


Fig.19. Variation in culm girth of six bamboo species at seventh year of growth (October 2022- October 2023) at Vellanikkara, Thrissur

In the present study, the number of culms per clump was found to be significantly different in different species (Fig.20). Among the six bamboo species maximum number of culms per clump was recorded for *D. asper* followed by *B. tulda,* and *D. longispathus* respectively. In general, the number of culms within a clump tends to be influenced by the culm girth, maintaining an inverse relationship. In other words, clumps with smaller culm girth can accommodate a higher number of culms, and this pattern was clearly evident in current study also. For example, bamboos with a higher number of culms per clump, like *D. asper*, *B. tulda*, and *D. longispathus*, exhibited lower culm girth measurements of 19.31 cm, 15.61 cm, and 13.58cm, respectively. The current findings align with a study conducted in Vellanikkara, Thrissur, where they also reported that *D. asper* (47) had the highest number of culms per clump (Amani *et al.,* 2022). In present study *B. balcooa* exhibited a notably low number of culms per clump (17.50). This finding aligns with the study conducted by Amlani *et al.,* 2017, where they similarly reported the lowest number of culms per clump for *B. balcooa* (9.67). However, it is important to highlight that the number of culms observed in the current study is higher compared to that reported by Amlani *et al.,* 2017, suggesting that agro-climatic conditions play a pivotal role in determining the growth and productivity of bamboo species.

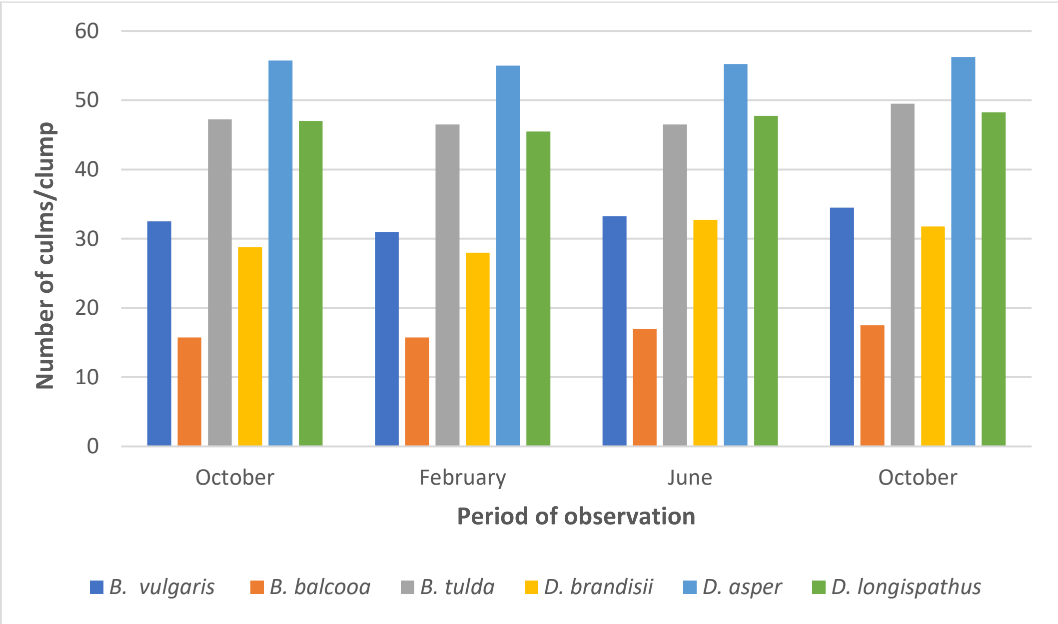


Fig.20. Variation in number of culms per clump of six bamboo species at seventh year of growth (October 2022- October 2023) at Vellanikkara, Thrissur

In the present study, the clump circumference was found to be slightly vary with different species (Fig.21). Among the six selected bamboo species highest clump circumference was observed in *B. vulgaris* followed by *B. balcooa* and *D. asper* respectively during final observational period. But in another study conducted within a two-year-old bamboo plantation in Thrissur, Kerala, there was a discrepancy with the current findings as *B. vulgaris* displayed the smallest clump circumference value (5.76) (Amani *et al.,* 2022). This observation raises the possibility that the rate at which the circumference of a clump expands for a particular species could be influenced by its age. The current findings align with a study conducted in Gujrat where they also reported that *B. vulgaris* (8.57m) had the highest clump circumference (Amlani *et. al* 2017).

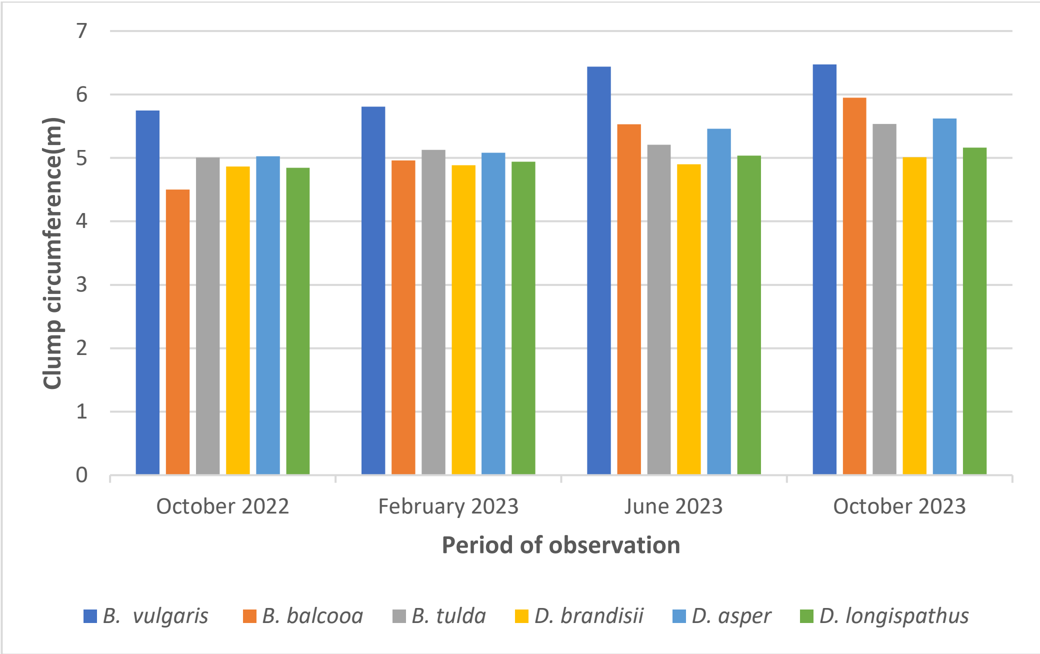


Fig. 21. Variation in clump circumference of six bamboo species at seventh year of growth (October 2022- October 2023) at Vellanikkara, Thrissur

In the present study internodal length was found to be significantly influenced by different bamboo species under all observational period (Fig.22). Among the six selected bamboo species *D. brandisii* displayed the highest internodal length followed by *D. asper* and *D. longispathus* respectively. Similar trends were observed by Getahun *et al.* (2023) where *D. asper* (37.9cm) recorded highest internodal length compared to other bamboo species. Amani *et al.* (2022) also observed the same trend where *D. brandisii* recorded highest internodal length followed by *D. asper*. It's worth noting that in contrast to the current findings, Amlani *et al.* (2017) reported a substantial internodal length for *B. tulda* (45.19cm), which is over twice the measurement we recorded in the current study (19.66cm), this might be attributed to different environmental conditions prevailing over the study areas.

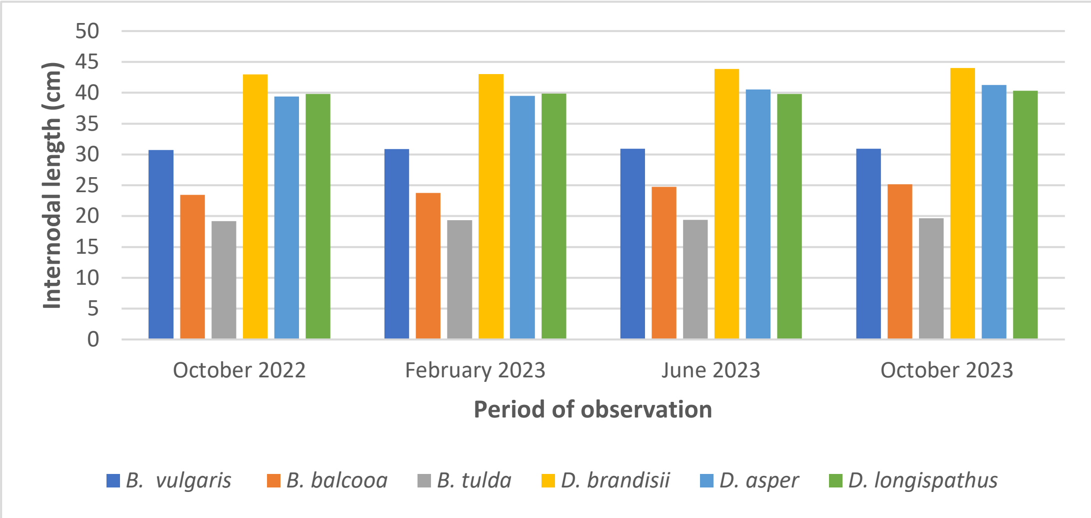


Fig. 22. Variation in internodal length of six bamboo species at seventh year of growth (October 2022- October 2023) at Vellanikkara, Thrissur

5.2. Litter dynamics

5.2.1. Litter quantification:

The quantity and seasonal trends of leaf litterfall and decomposition play crucial roles in the overall nutrient cycling and preservation of soil fertility in terrestrial ecosystems (Tripathi *et al.,*2006) The rate of litterfall production results from the interplay between the genetic characteristics of trees and the impact of environmental factors, making it a potential indicator of the health of a forest (Zhou *et al.,* 2007).

In the present study, the annual litter production for the following bamboo species: *B. vulgaris, B. balcooa, B. tulda, D. brandisii, D. asper,* and *D. longispathus*, ranged from approximately 9.64 to 6.98, 7.3, 7.8, 8.05, and 9.59 Mg ha^{-1} $year^{-1}$, respectively. Among the six selected species, the sequence of litter production was as follows: ***Bambusa vulgaris* > *Dendrocalamus longispathus*> *Dendrocalamus asper* > *Dendrocalamus brandisii* > *Bambusa tulda* > *Bambusa balcooa*.** The annual litter production observed in the current study for *B. vulgaris* (9.64 Mg ha^{-1} $year^{-1}$) and *B. balcooa* (6.98 Mg ha^{-1} $year^{-1}$) is lower than the yearly litter production reported for *B. vulgaris* (12.1 Mg ha^{-1} $year^{-1}$) and *B. balcooa* (11.7

Mg ha^{-1} $year^{-1}$) in Uttarakhand (Kaushal *et al.,* 2020). Nevertheless, it's worth highlighting that in both studies, *B. vulgaris* consistently exhibited higher litter production than *B. balcooa*, indicating a pronounced influence of the species on litter production**.**

Litterfall displayed a bimodal pattern, except in the case of *B. balcooa,* where it exhibited a trimodal pattern. The primary peak in litterfall was consistently observed after N-E monsoon, during the winter months of December to January, with a secondary, smaller peak occurring in June or July. Similar patterns have been observed by many researchers Jijeesh and Seethalakshmi,2016a; Hua *et al.*,2014; and Kunhamu *et al.,* 2009. The examination of litterfall data revealed significant fluctuations in seasonal litter production among various bamboo species. Interestingly, more than half of the total annual litter production in all the selected bamboo species occurred between November to February. This increased litterfall during the November to February period aligns with the findings of Jijeesh and Seethalakshmi (2015), where they also observed a substantial increase (over 70%) in litterfall for *B. balcooa* during November to March, contrasted with lower litterfall during the rainy season. Jamaludheen and Kumar (1999) noted that the highest litterfall occurs from November to February, likely attributed to the natural senescence of leaves caused by temperature and moisture stress in the area. Tripathi and Singh (1995) also observed that the highest litterfall in savanna bamboo occurred during winter months of November to February (64-65%). Meteorological data (Table 1) reveals that the months (November to February) experienced a decrease in both rainfall and rainy days. Zhang *et al.* (2017) similarly affirmed the significant impact of rainfall, on litter production in Moso Bamboo. The winter season primarily induces water stress due to reduced water availability. Consequently, it can be inferred that the periodicity of litterfall is in general, a consequence of water stress. The present investigation also yielded a similar trend, underscoring the dominant influence of climatic factors on litter production.

In present study, a clear dominance of leaf litter was observed, constituting more than 70 percent of the total litterfall in all bamboo species. Particularly in *B.*

tulda, leaves accounted for more than 75.94 percent of the total litter produced. Following leaves, twigs made the most substantial contribution to the overall leaf fall, amounting to over 16 % of the total litterfall. The order of contribution among litter components was as follows: leaves > twigs > sheath. These findings are consistent with previous studies by Hua *et al*. (2014); Jijeesh and Seethalakshmi (2015), and Scarascia *et al.* (2000). However, the current study noted a slightly higher twig contribution compared to some other researchers. Jamaludheen (1994) also reported high contribution of twigs to total litter in *Paraserianthes* (27.4%). This increased twig contribution in total litterfall is a characteristic feature of middle-aged bamboo stands, where branch mortality tends to be higher (Laskowski and Berg, 2006).

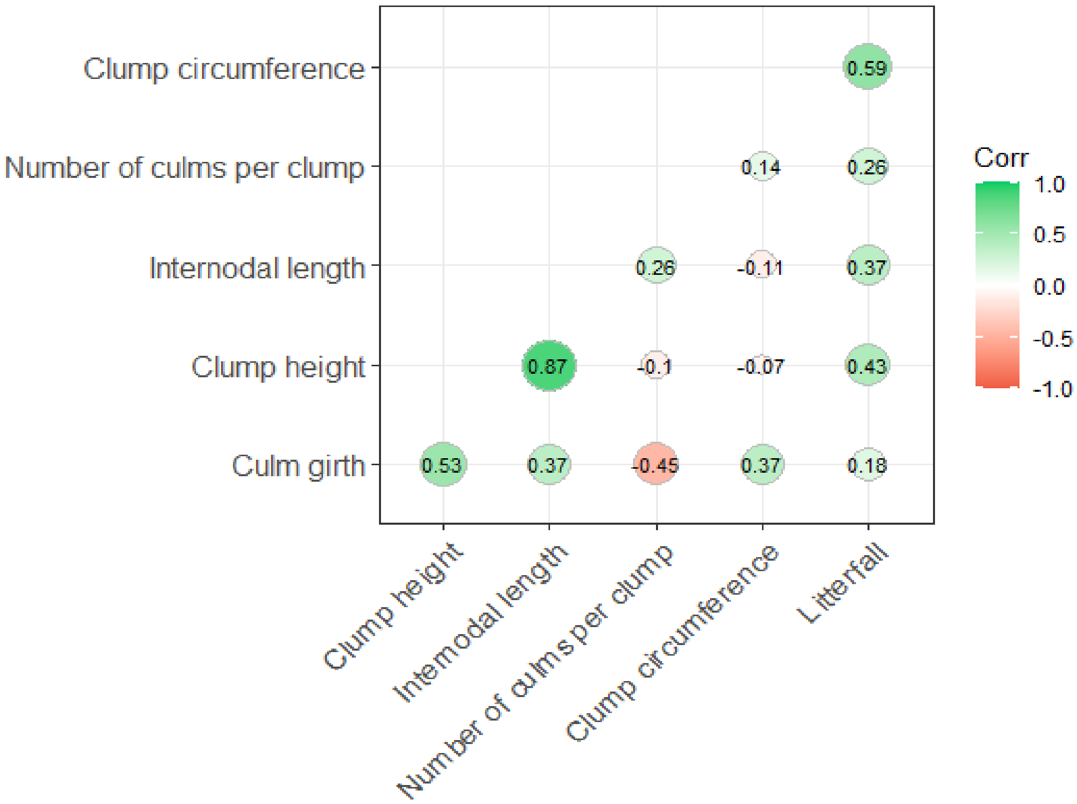


Fig. 23. Correlation analysis between bamboo growth parameters and total annual litterfall at Vellanikkara, Thrissur

Perusal of literature suggests that there exists a strong relation between litter production and stand basal area (Kumar,2008). In the present study, a correlation analysis was conducted between litterfall production and various growth parameters of bamboo (Fig. 23). The analysis indicates a moderately positive correlation (r= 0.59) between clump circumference and litterfall. This correlation may explain the higher litterfall production observed in *B. vulgaris*, where the clump circumference was the greatest (5.75m), and the lowest in *B. balcooa*, where the clump circumference was comparatively lower (4.50m). Kunhamu *et al.* (2009) also observed a strong positive relationship between litterfall production and stand basal area in 9-year-old *Acacia mangium* stand. Similarly, George and Kumar (1998) noticed a strong positive correlation between crown diameter and litterfall production in four tree species cultivated under a silvipastoral system in Palakkad, Kerala.

In the current study, the annual litterfall recorded for six bamboo species falls within the observed range of litterfall for fast-growing tree species and other traditional plantation trees in Kerala.

Table 33: Total annual litterfall of different bamboos and other plantation tree species grown in Kerala

Species	**Age (Year)**	**Location**	**Litterfall (Mg ha $^{-1}$year $^{-1}$)**	**Reference**
Paraserianthes falcataria	8-9	Palakkad	9.17	Jamaludheen and Kumar (1999)
Pterocarpus marsupium	8-9	Palakkad	3.42	Jamaludheen and Kumar (1999)
Acacia auriculiformis (Pruned silvipastoral system)	5-6	Palakkad	6.27	George and Kumar (1998)
Casuarina equisetifolia	5-6	Palakkad	2.31	George and Kumar (1998)

(Pruned silvipastoral system)				
Leucaena leucocephala (Pruned silvipastoral system)	5-6	Palakkad	2.30	George and Kumar (1998)
Leucaena leucocephala (woodlot plantation)	8-9	Palakkad	5.09	Jamaludheen and Kumar (1999)
Ailanthus triphysa (Pruned silvipastoral system)	5-6	Palakkad	1.92	George and Kumar (1998)
Ailanthus triphysa (woodlot plantation)	8-9	Palakkad	4.57	Jamaludheen and Kumar (1999)
Acacia auriculiformis	6	Thrissur	12.9	Kunhamu *et al.* (1994)
Moist deciduous natural forests	Unknown	Palakkad	12.2 to 14.4	Kumar and Deepu (1992)
Acacia mangium	9	Palakkad	5.73 to 11.18	Kunhamu *et al.* (2009)
Mangrove forest	Unknown	Kunhimangalam	11.39	Shanij *et al*. (2023)
Ochlandra travancorica	6	Palakkad	1.84	Jijeesh and Seethalakshmi (2016b)
Theobroma cacao + *Hevea brasiliensis*	7	Thrissur	5.32	Sreekala (1997)
Theobroma cacao	7	Thrissur	8.32	Sreekala (1997)
Bambusa balcooa	6	Palakkad	4.06	Jijeesh and Seethalakshmi (2016a)
Munrochloa ritcheyi	Unknown	Nilambur	2.84	Kuruvilla *et al.* (2016)

Table 33 reveals that the six bamboo species selected in the current study, produced a substantial quantity of litter. The litter production aligns with, and sometime surpasses the litter production observed in other fast growing tree species and traditional tree plantations in Kerala. This observation underscores the significant contribution of bamboo to nutrient cycling, as the high litterfall signifies a high influx of organic matter into the soil, thereby contributing significantly to the enhancement of soil health.

5.2.2. Litter decomposition:

The litter that falls onto the soil goes through various stages of decomposition, which are influenced by both the characteristics of the substrate and the prevailing climatic conditions (Tripathi and Singh, 1992). Initial substrate chemistry of litter significantly influences both the mass loss and decomposition processes. The quality of plant litter in terms of decomposition can be described as its degree of ease in being mineralized by decomposing organisms (Edmonds (1984); Berg *et al*. (1987), and Paustian *et al.* (1997)). Multiple studies on litter have demonstrated that the C/N ratio and the initial nitrogen concentration are reliable indicators for predicting litter decomposition (Taylor *et al*. (1989b)). A nitrogen concentration exceeding 2.5% signifies a higher rate of nitrogen mineralization due to quicker decomposition. In present study, the sequence of nitrogen content in litter across various bamboo species was as follows: *B. tulda* > *B. balcooa* > *B. vulgaris* > *D. longispathus* > *D. asper* > *D. brandisii*. Notably, *B. tulda* exhibited a relatively higher nitrogen concentration of 2.42%, which could be a contributing factor to its faster decomposition. Conversely, nitrogen levels below 2% can limit the decomposition of tropical litters, as suggested by Seneviratne (2000), and this might be a contributing factor to the comparatively slower decomposition of other bamboo litter types.

Litter decomposition involves two concurrent processes: (a) the associated mineralization and humification of substances like lignin and cellulose, carried out by microorganisms, and (b) the gradual release of soluble compounds into the soil, where their carbon and nitrogen components undergo stepwise mineralization

(Anderson,1988), immobilization of litter nutrients is commonly described as a three-stage process: initially, soluble nutrients leach from the litter; then, there's a phase of nutrient immobilization; and finally, net nutrient mineralization occurs, making the nutrients available for plant uptake once again (O'Connell and Sankaran, 1997). In the present study, we observed a three-phase decomposition pattern (consisting of an initial faster phase, followed by an intermediate slower phase, and concluding with a terminal fast phase) for all the six bamboo species. The likely reason for this pattern may be attributed to the fact that the litter was incubated well in advance before the rainy season. The three-phase decomposition pattern observed in the current study corresponds with the results reported by Sujatha *et al.,* 2003. They, too, noted a similar pattern when the litter was incubated well in advance of the rainy season. Throughout the decomposition process, there was a periodic and consistent loss of mass over time. After 12 months (360 days) of field incubation, the remaining mass of selected bamboo litter ranged from 0.6% to 16.35% of the initial mass. Regression analysis was employed to examine the relation between the duration after incubation(months) and the degree of litter decomposition. Litter mass, presented as a percentage of its initial dry weight, demonstrated an exponential decline over time. The decomposition rates in various bamboo species were well-suited to Olson (1963) exponential decay model. The resulting decay equations for these distinct bamboo species are as follows:

1	*Bambusa vulgaris*	$x=x_o/e^{-0.136t}$
2	*Bambusa balcooa*	$x=x_o/ e^{-0.123t}$
3	*Bambusa tulda*	$x=x_o/ e^{-0.292t}$
4	*Dendrocalamus brandisii*	$x=x_o/ e^{-0.127t}$
5	*Dendrocalamus asper*	$x=x_o/ e^{-0.196t}$
6	*Dendrocalamus longispathus*	$x=x_o/ e^{-0.126t}$

In the present study decay rate between selected species ranged from 0.123 to 0.292. This variation in decay rate might be explained by inter- and intraspecific variation in leaf litter quality (Giweta, 2020). The rate of litter decomposition in different bamboo species was in the following order ***B. tulda* > *D. asper* > *B. vulgaris* > *D. brandisii* > *D. longispathus* > *B. balcooa***. The faster decomposition rates observed in the litter mass of *B. tulda* could be linked to the existence of readily leachable substances in the litter. Furthermore, the initial litter concentration, characterized by a higher nitrogen content, facilitated its relatively faster decomposition. In line with this, Deb *et al.* (2005) similarly found that *B. tulda* exhibits a faster decomposition rate compared to *D. hamiltonii* in bamboo-based agroforestry system in Northeast India. and they attributed this faster decomposition rate to the higher nitrogen levels and lower lignin content in *B. tulda*. In the current study, *B. vulgaris* demonstrated a higher decay rate in contrast to *B. balcooa*. However, this outcome contradicts the results reported by Akoto *et al.* (2022), where they observed a higher decay rate constant in *B. balcooa* compared to *B. vulgaris*. This variance suggests that environmental conditions may play a significant role in influencing the decay rate.

Table 34: The monthly litter decomposition rate (k) and half-life (k) of different fast-growing trees or plantation species in the Kerala

Species	**Location**	**k value**	**Half-life ($month^{-1}$)**	**Reference**
Acacia auriculiformis	Palakkad	0.16	4.2	Jamaludheen and Kumar (1999)
Ailanthus triphysa (silvipastoral system)	Palakkad	0.14	4.8	George and Kumar (1998)
Artocarpus heterophyllus	Palakkad	0.22	3.1	Jamaludheen and Kumar (1999)

Artocarpus hirsutus	Palakkad	0.21	3.4	Jamaludheen and Kumar (1999)
Casuarina equisetifolia	Palakkad	0.17	4.0	Jamaludheen and Kumar (1999)
Leucaena leucocephala	Palakkad	0.29	2.4	Jamaludheen and Kumar (1999)
Paraserianthes falcataria	Palakkad	0.20	3.4	Jamaludheen and Kumar (1999)
Phyllanthus emblica	Palakkad	0.18	3.9	Jamaludheen and Kumar (1999)
Pongamia pinnata	Kerala	0.28	2.46	Kunhamu *et al.* (1994)
Tectona grandis	Thrissur	0.167	4.2	Sankaran (1993)
Theobroma cacao	Thrissur	0.21	3.28	Sreekala (1997)
Swietenia macrophylla	Thiruvananthapuram	2.04	5.8	Isaac and Nair (2006)
Ochlandra travancorica	Palakkad	0.42	1.65	Jijeesh and Seethalakshmi (2016b)
Bambusa balcooa	Palakkad	0.34	2.57	Jijeesh and Seethalakshmi (2016a)
Munrochloa ritcheyi	Nilambur	0.27	2.57	Kuruvilla *et al.* (2016)
Eucalyptus tereticornis	Thrissur	0.061	11.2	Sankaran (1993)
Paraserianthes falcataria	Thrissur	0.139	5.0	Sankaran (1993)

Table 34 indicates that, among the six bamboo species selected for the study, most exhibit a moderate rate of decomposition. Notably, *B. tulda* stands out with a comparatively faster decomposition rate, aligning with the rate observed in certain fast-growing tree species in Kerala. Furthermore, bamboo species surpass even dominant plantation tree species like teak and Eucalyptus in decomposition rate. Conversely, certain species in the study demonstrate a more moderate rate of decomposition, suggesting the potential for these species to serve as organic mulch materials. This could lead to the gradual improvement of soil physicochemical properties through the accumulation of organic matter over time (Isaac and Nair,2006).

5.2.2.1. Nutrient dynamics in decomposing litter

In the current study, the concentration of nutrients and the percentage of remaining nutrients, specifically nitrogen, phosphorous, and potassium, in the residual litter mass (collected at monthly intervals) exhibited significant variability. The release of nutrients from the decomposing litter either follow one of two patterns: a triphasic pattern characterized by an initial accumulation, followed by a rapid release, and a final slower phase, or a biphasic pattern lacking the initial accumulation phase (Krishna and Mohan, 2017). In present investigation, all selected bamboo species displayed a triphasic pattern for nitrogen, showing an initial decline in nitrogen concentration, followed by an increase, and finally, a subsequent decline. Jamaludheen and Kumar,1999 also noted a three-phasic model for the release of nutrients during the decomposition of litter. The decrease in nitrogen concentration with time could be attributed to its potential loss through leaching. In the current study, there was a rise in nitrogen concentration from February to April. This increase in nitrogen levels might be attributed to processes such as microbial nitrogen fixation, microbial immobilization, or throughfall. A similar pattern was noted in B. *balcooa* and *O. travancorica* in studies conducted by Jijeesh and Seethalakshmi (2016a); Jijeesh and Seethalakshmi (2016b). The current findings also align with the results reported by Isaac and Nair (2006) for multipurpose tree species.

The nitrogen content in the decomposing litter also displayed a triphasic pattern of nutrient release, involving initial loss, immobilization, and eventual release. The highest nitrogen release within one month was observed in *B. tulda*, where 65.58% of the initial nitrogen content was released. This substantial release could be attributed to the initially high nitrogen concentration, as an initial nitrogen content exceeding 2.5% indicates a faster rate of nitrogen mineralization due to accelerated decomposition (Uthappa, 2021). The influence of initial nitrogen concentration on the rate of nitrogen mineralization was consistent with the findings in the current study.

The phosphorus concentration during the decomposition of different bamboo species did not exhibit a particular pattern, which aligns with the observations made by Kaushal *et al.* (2012) in the four multipurpose tree species. In case of *B. vulgaris, B. balcooa,* and *D. longispathus* there was an initial immobilization in phosphorus concentration. This could be attributed to the incubation of litter samples prior to the rainy season, as noted by Sujatha *et al.* (2003) in the case of *O. travancorica*. This trend of increasing initial phosphorus concentration in decomposing litter was also reported by Awasthi *et al.* (2022) in the case of *Coriaria nepalensis*, suggesting that phosphorus immobilization was necessary until a critical concentration for decomposition was achieved. They also highlighted that phosphorus was less affected by leaching. Rutigliano *et al*. (1998) suggested that the rise in phosphorus may result from microbial immobilization, as it was a limited resource. Interestingly, in the current study, the phosphorus concentration in bamboo soil was found to be lower than the typical value for this site, which could be one of the reasons for the initial immobilization of phosphorus.

The phosphorus content within the decomposing litter generally followed a triphasic pattern of nutrient release, involving initial loss, immobilization, and eventual release. However, in the case of *B. vulgaris, B. balcooa,* and *D. longispathus*, there was an initial immobilization of phosphorus concentration. The current findings contrast with those of Jijeesh and Seethalakshmi (2016a), who observed an initial release of phosphorus in decomposing *B. balcooa* litter when it was placed for decomposition during the rainy season. This suggests that environmental factors can strongly influence the pattern of phosphorus release.

The potassium concentration during the decomposition of litter in selected bamboo species also exhibited a triphasic pattern, characterized by an initial decline, followed by an increase in concentration, and final release. This finding is consistent with previous studies on litter decomposition by Thomas *et al.,* 2014, Jijeesh and Seethalakshmi (2016a), and Nath and Das (2011). Potassium is easily leached from leaf litter because it is highly soluble, as noted by Guo *et al*. (2009), and it tends to be concentrated in cells located close to the leaf surface, as mentioned by Waring and Schlesinger (1985). Nath and Das (2011) identified it as the most mobile element, which explains its rapid release during decomposition. In present study, a notable initial loss of potassium was observed, for e.g., 71.5% of K was released within one month of decomposition in *B. vulgaris*. This can be attributed to the fact that potassium is not bound to any structural component, making it easily leachable. In contrast, Isaac and Nair (2005) noted a continuous release pattern of potassium in decomposing litter without any immobilization.

The correlation analysis (Fig. 24) unveiled that the decay rate (k) exhibited a moderate positive correlation with the initial litter nitrogen concentration (r = 0.58) and a negative correlation with the initial litter C:N ratio (r = -0.56). This observation likely explains the observed faster decomposition rate in *B. tulda*, where a higher initial nitrogen concentration and a comparatively lower initial C:N ratio were noted in the litter. The C/N ratio is recognized as a reliable predictor of litter decomposition, with a ratio of less than 20 or nitrogen concentration exceeding 2.5% indicating accelerated nitrogen mineralization due to faster decomposition, while higher C/N ratios can lead to nitrogen immobilization, slowing down litter decomposition (Taylor *et al.,* 1989a; Torreta and Takeda, 1999). Myers *et al.* (1994) reported that substrates with C/N < 25 are considered of high quality, releasing mineral nitrogen more rapidly than those with C/N > 25.

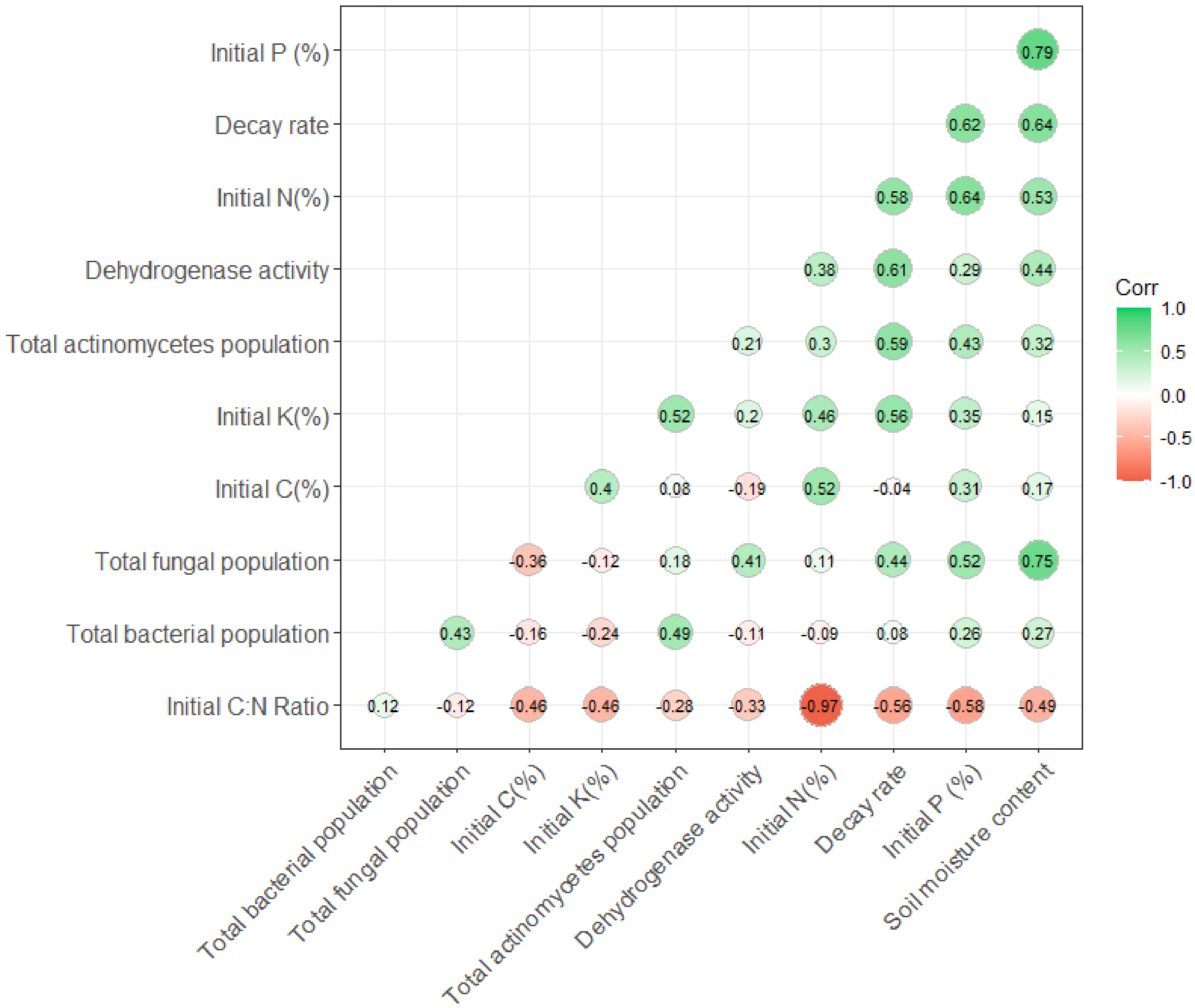


Fig. 24. Correlation analysis between initial litter nutrients concentration, decay rate constant, soil moisture content and soil biological properties at Vellanikkara, Thrissur

Additionally, the decay rate (k) also displayed a moderate positive correlation with dehydrogenase activity (r=0.61), soil total fungal population (r=0.44), and soil moisture content (r= 0.64). This could account for the faster decomposition rate observed in *B. tulda*, as it exhibited the highest dehydrogenase activity, soil moisture content, and soil fungal population. This aligns with findings by Kumar *et al*. (2010) and Pant and Tiwari (1992), who noted higher rates of litter decomposition during rainy seasons attributed to elevated soil moisture and increased fungal activity.

5.3. Physico chemical properties of soil under six bamboo species

5.3.1. Bulk density

In present study, the soil bulk density beneath the selected bamboo species was significantly lower than that in the adjacent open plot during both sampling periods (Fig.25). The notably higher bulk density in the open plot, as compared to the bamboo species, can likely be attributed to soil compaction and the absence of organic matter in the open plot. This aligns with the findings of Gaikwad *et al.* (2022a), where they also observed relatively lower bulk density under bamboo plots when compared to open plots. The reduced bulk density under bamboo can be linked to the significant organic matter contributed by bamboo and the extensive fine bamboo roots, both of which increase the pore space and, consequently, reduce the bulk density under bamboo. Similar results were reported by Singh *et al*. (2012), who noted higher bulk density in open areas compared to areas with other tree species.

In the current study, we noticed that bulk density increased with soil depth also and the highest bulk density recorded at the lowest depth across all bamboo species. This increase in bulk density with depth can be attributed to several factors, including a reduction in pore space, a higher presence of gravel, reduction in aggregation, and lower organic matter content in comparison to the surface soil (Doerr *et al.* (2000)). Similar trend of increasing bulk density with increasing depth was also observed by Samritika (2013). When comparing the initial and final sampling, slight decrease in bulk density beneath the bamboo was noticed. This observation is consistent with the results reported by Nath *et al.* (2015), where they also observed a slight decrease in bulk density as bamboo aged. This decline can be attributed to the increasing amount of soil organic carbon (SOC) due to the increased input of root biomass and litterfall, which tends to increase as the bamboo clump matures.

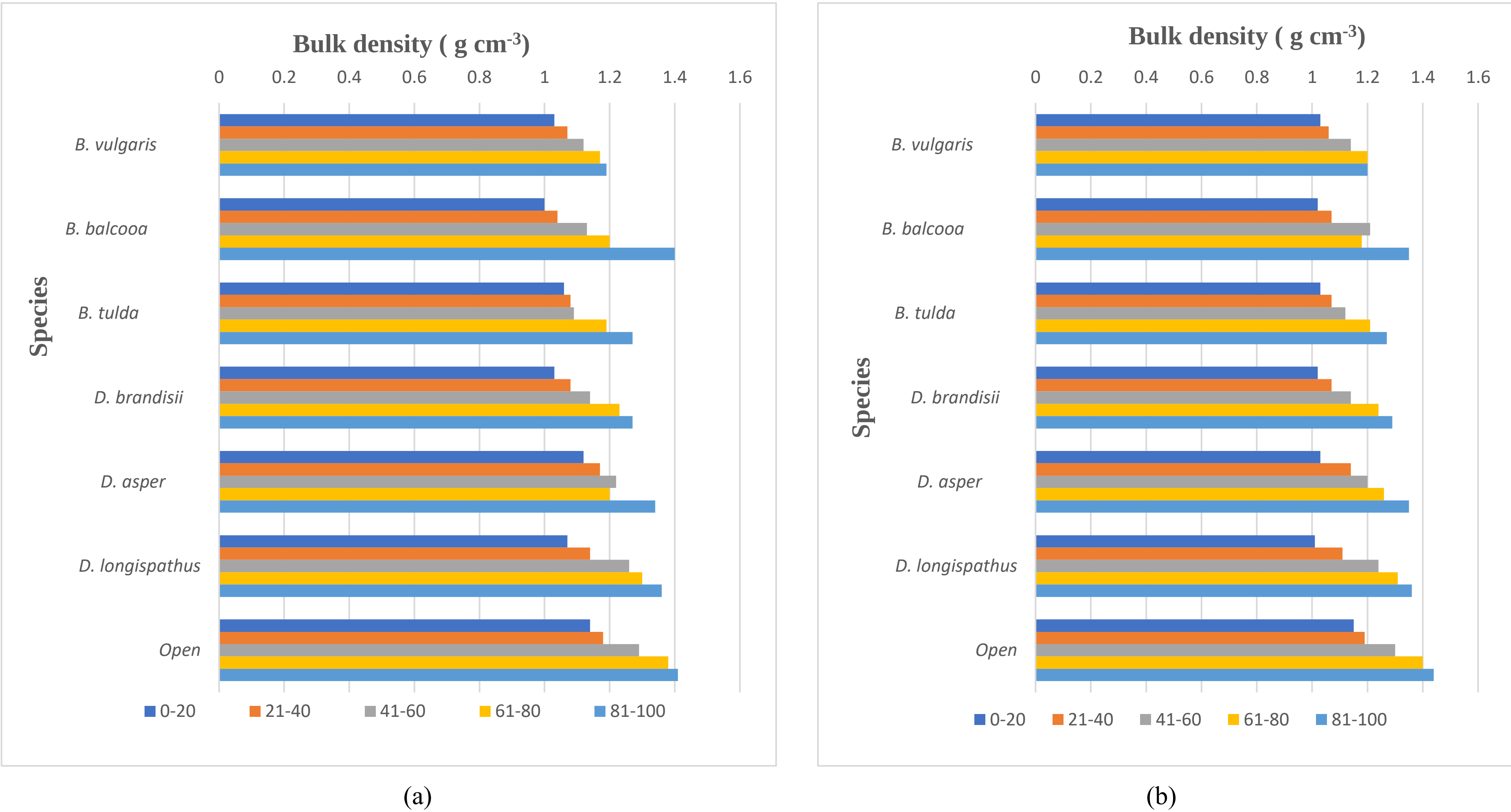


Fig.25. Soil bulk density (g cm^{-3}) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

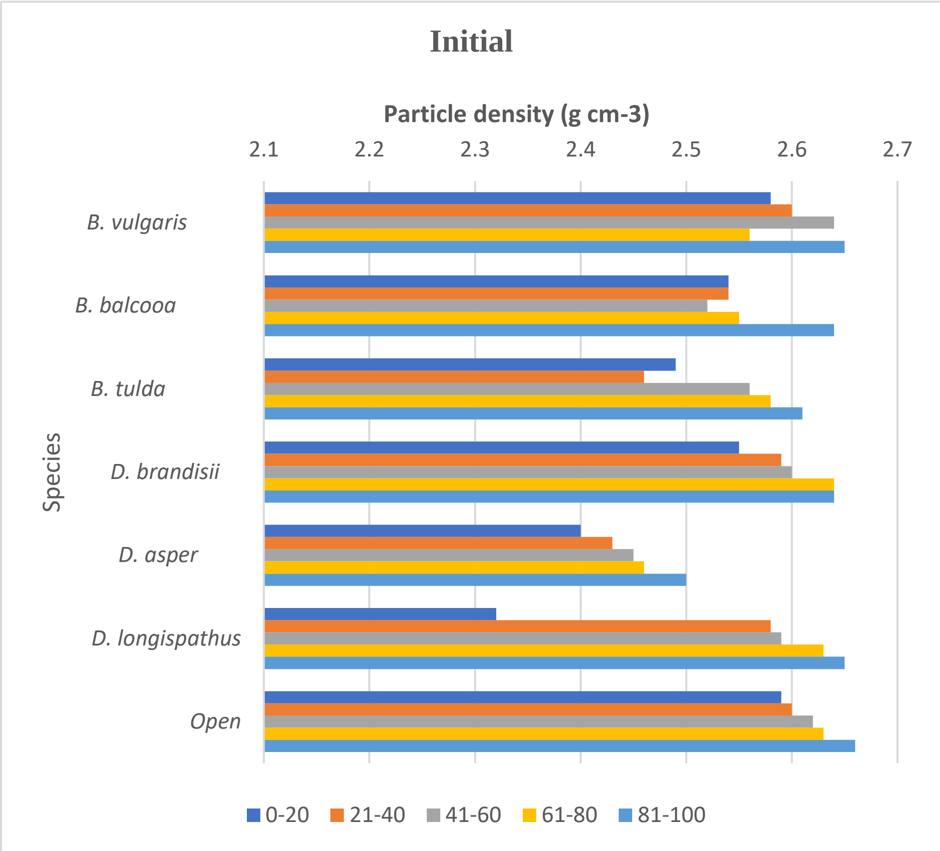
a) Initial sampling b) final sampling

5.3.2. Particle density

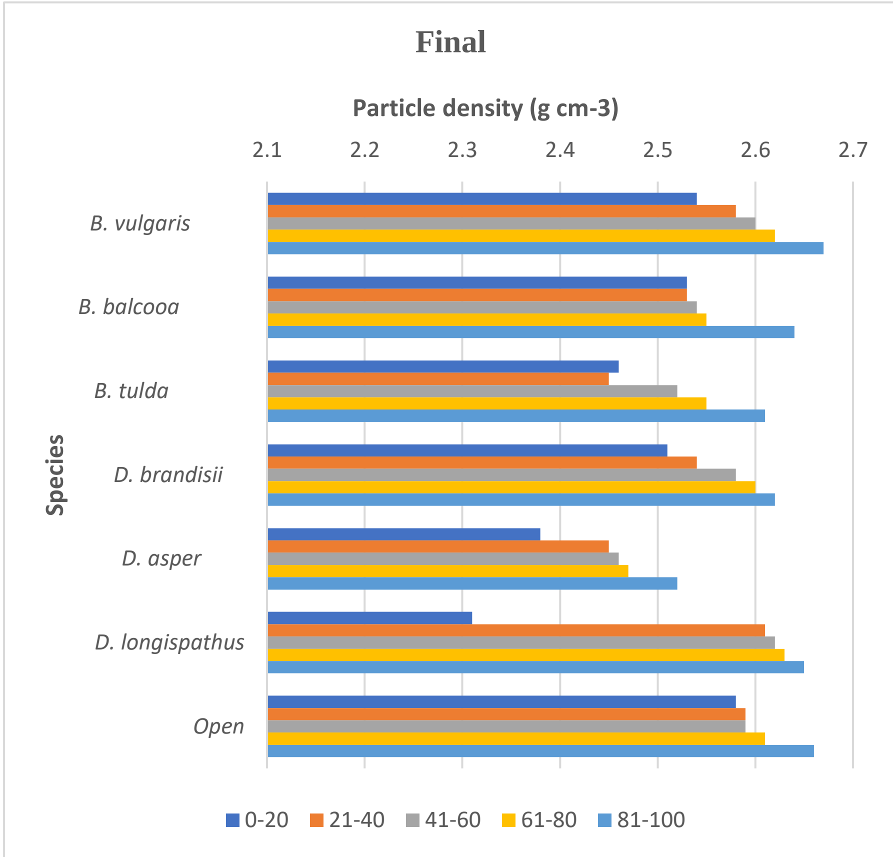
In present study, the soil particle density beneath the selected bamboo species remained relatively consistent across both sampling periods (Fig.26). Interestingly, a slightly higher value of particle density was noted in the open plot as compared to the bamboo plots. This observation is in line with the findings of Selassie and Ayanna (2013), who also reported higher particle density in open plots compared to tree-based land use systems. This might be attributed to the removal of finer soil particles through erosion in unprotected lands, resulting in a higher proportion of coarser particles, particularly sand, which elevates particle density. Furthermore, the current study also revealed that particle density increased with soil depth, similar trend was observed in several other studies (Narendra, 2017; Dinesh, 2015). This increase could be attributed to the decrease in soil organic matter content with depth, as noted by Selassie and Ayanna (2013). When comparing the initial and final sampling values, there wasn't a significant difference in particle density beneath the bamboo.

5.3.3. Soil Porosity

In present study, the soil porosity doesn’t vary significantly between the selected bamboo species, and it also remained relatively consistent across both sampling periods (Fig.27). Interestingly, a lower porosity was noted in the open plot as compared to the bamboo plots. This might be due to higher soil organic matter under bamboo plantation compared to open plot. Similar trend was observed in other studies also (Singh *et al.*,2012, Selassie and Ayanna (2013). An inverse relationship between bulk density and soil porosity was also observed under the present study. Consequently, as soil bulk density increased with depth, it led to a decrease in porosity. This might be attributed to the compaction induced by the weight of the surface soil layer in the lower layers, resulting in a reduction in porosity. When comparing the initial and final sampling values, there wasn't a much difference in soil porosity beneath the bamboo.

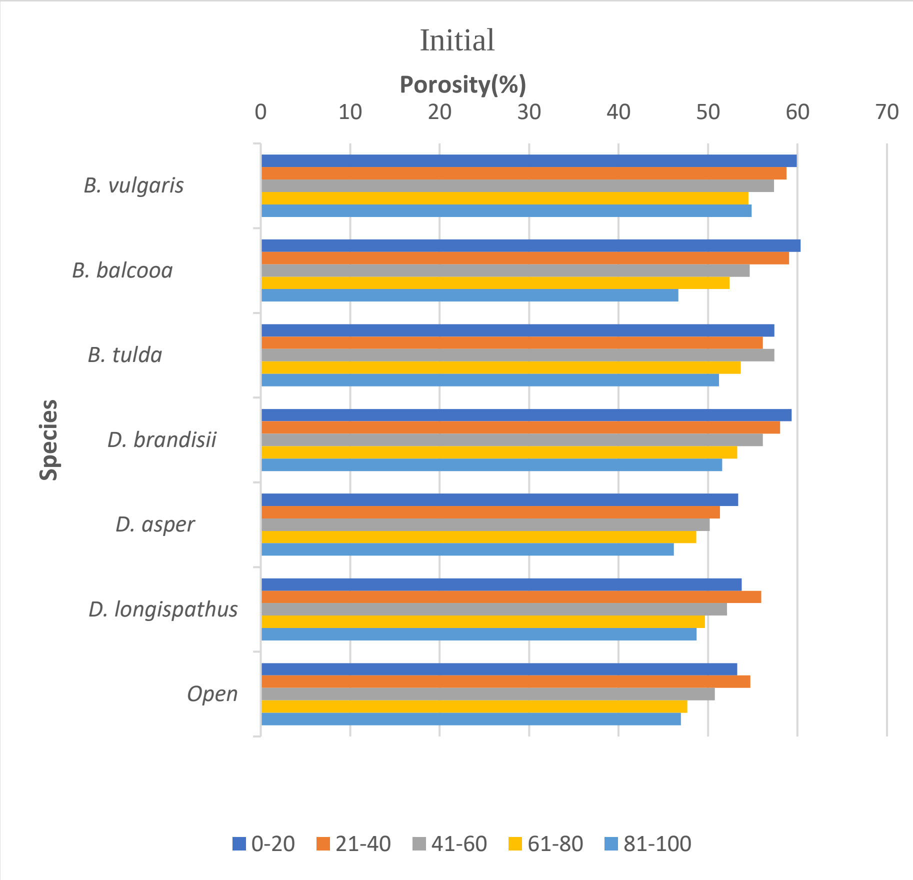


(a)

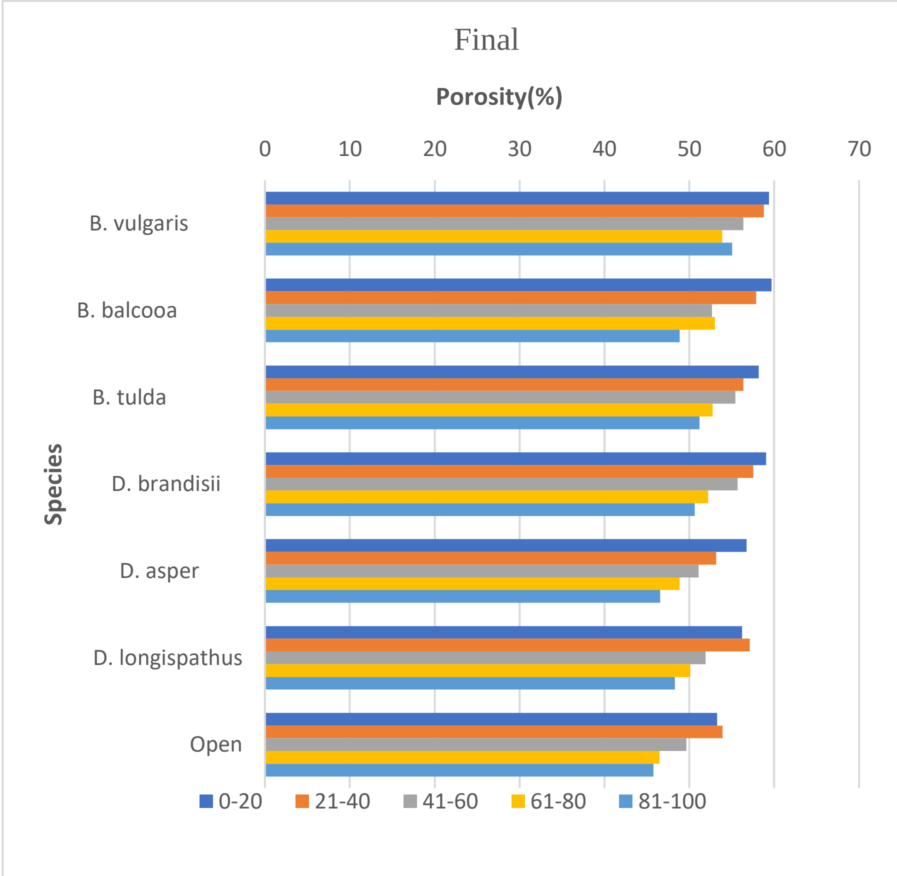


(b)

Fig.26. Soil particle density (g cm^{-3}) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur a) Initial sampling b) final sampling

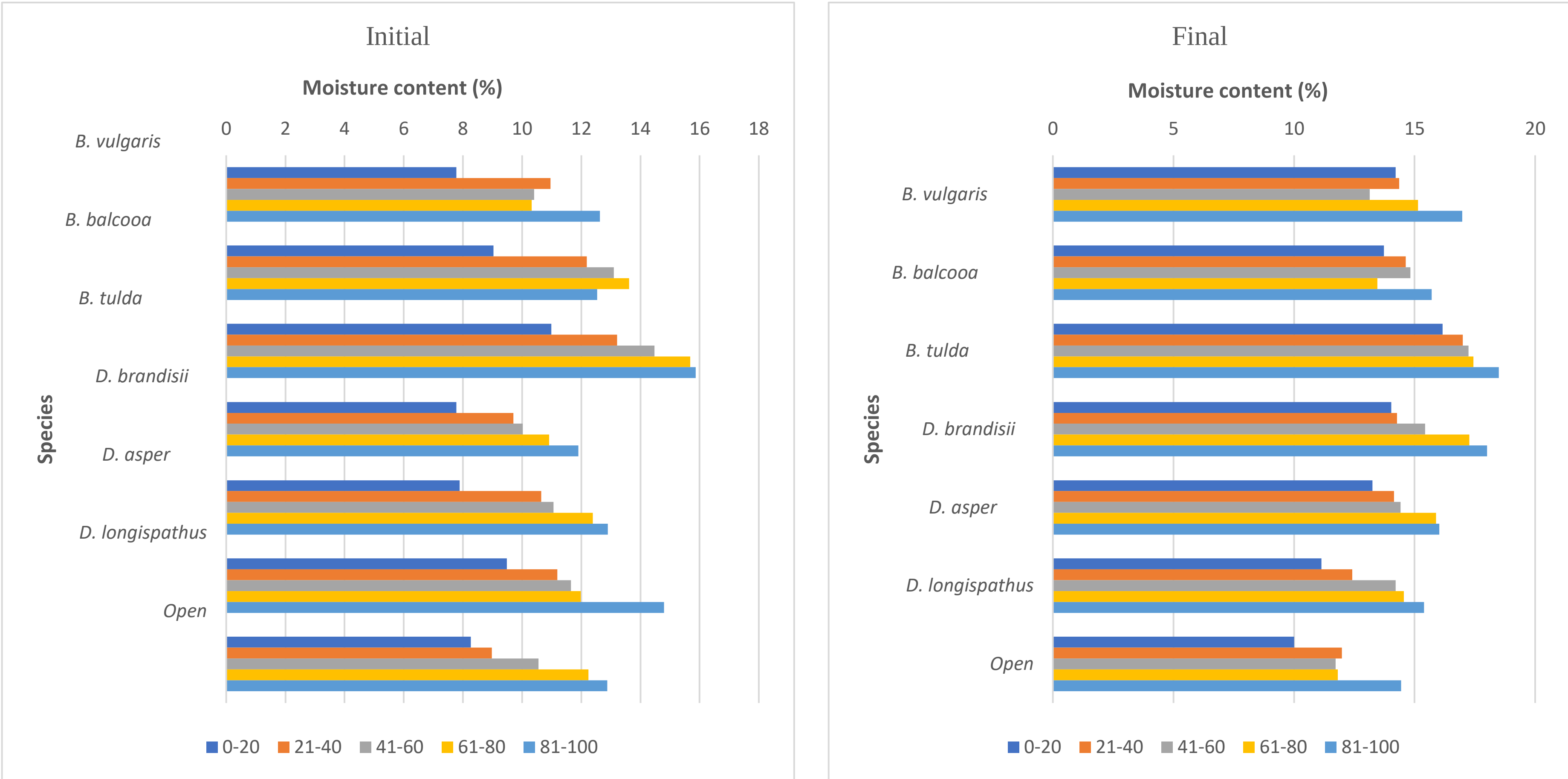


(a)



(b)

Fig.27. Soil porosity (%) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur a) Initial sampling b) Final sampling



(a) (b)

Fig.28. Soil moisture content (%) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur a) Initial sampling b) final sampling

5.3.4. Soil Moisture

In present study, the soil moisture beneath the six bamboo species was generally higher than that in the adjacent open plot during both sampling periods (Fig.28). However, in the case of *B. vulgaris*, *D. brandisii*, and *D. asper*, there was a slight decrease in soil moisture in the upper soil layer compared to the open plot, but this was only during the first sampling season. This reduction in surface soil moisture is likely due to the high density of fine roots in these species in the upper soil layer, which may lead to increased water absorption in the surface soil. This phenomenon aligns with the findings of Kaushal *et al.* (2020), who observed very high coarse root biomass (287.6 g m^{-2}) and fine root biomass (996.4 g m^{-2}) under *B. vulgaris* in the upper soil. In the current study, we observed a consistent pattern of increasing soil moisture content with increasing soil depth, with the highest moisture content consistently found at the lowest layer across all bamboo species. Similar trends are also observed by Dey *et al.*, 2023 which might be due to the infiltration of water from surface to the bottom layer Additionally, the upper soil layers tend to have a higher intensity of roots compared to lower depth, which might have increase water absorption in the upper layers. These observations align with the results reported by Bai *et al.,* 2023.

During both sampling periods, the highest moisture content was consistently observed under *B. tulda*, possibly due to the more extensive canopy cover provided by *B. tulda* compared to other species. In the second sampling, all bamboo species recorded higher moisture content than the open plot. This might be due to combined effect of increased shading and the presence of leaf litter, which acts as a mulch, reducing evaporation from the surface soil (Gogoi and Bhuyan,2016 and Garima,2013). Furthermore, in comparison to the initial sampling, increased moisture content was observed in all bamboo species during sampling. This increase could be attributed to the monsoon showers that occurred during the month of July and August.

5.3.5. Soil pH and EC

In present study, the soil pH beneath the selected bamboo species was significantly lower than that in the adjacent open plot during both sampling periods (Fig.29). The open plot exhibited the highest pH values, while the reduced pH in the bamboo plots can be attributed to several factors like root respiration, along with the accumulation and slow decomposition of organic matter, results in the release of acids, making bamboo soil more acidic compared to the open plot (Dey *et al.*,2023). Singh *et al.,* 2012 also reported lower pH values in the soil under different tree species compared to adjacent open plots. The result of present study showed pH increases with increasing soil depth, which might be due to the leaching of salts and their subsequent deposition in the lower soil layers. This pattern is consistent with the observations of Dey *et al*., 2023, where they reported that the presence of high organic matter in the surface soil can contribute to the increased acidity of the topsoil. Similar trends were also reported by Bhardwaj *et al.*, 2001 and Singh *et al.,* 2012. Compared to the initial values, the soil pH increased in the final sampling. This is in line with the results obtained by Nath *et al.*, 2015, where soil pH under bamboo plantation increased with the age of the plantation. Similar results were also observed by Kaushal *et al.,* 2020, where they have observed 0.13 increase in soil pH under *Bambusa balcooa*.

The soil EC did not vary significantly between different bamboo species during both sampling period (Fig.30). In present study, lower values of EC were observed. Similar findings were also reported by Gogoi and Bhuyan (2016). The results in present study showed decrease in EC with increasing soil depth. This decline in EC with depth is likely due to the presence of a significant amount of litter on the surface, which, upon decomposition, releases salts into the surface layer. This pattern is consistent with the observations of Dey *et al.*, 2023. Mohd-Aizat *et al.,* 2014 found a negative relationship between EC and pH, as in present study pH increased with depth, that might have led to decrease in EC with depth. In contrast to the initial values, the soil EC increased in the final sampling. Similar trends were reported by Nath *et al*., 2015, and this increase in EC can be attributed to the increased input of root biomass and litterfall, which tends to rise with the age of the plantation.

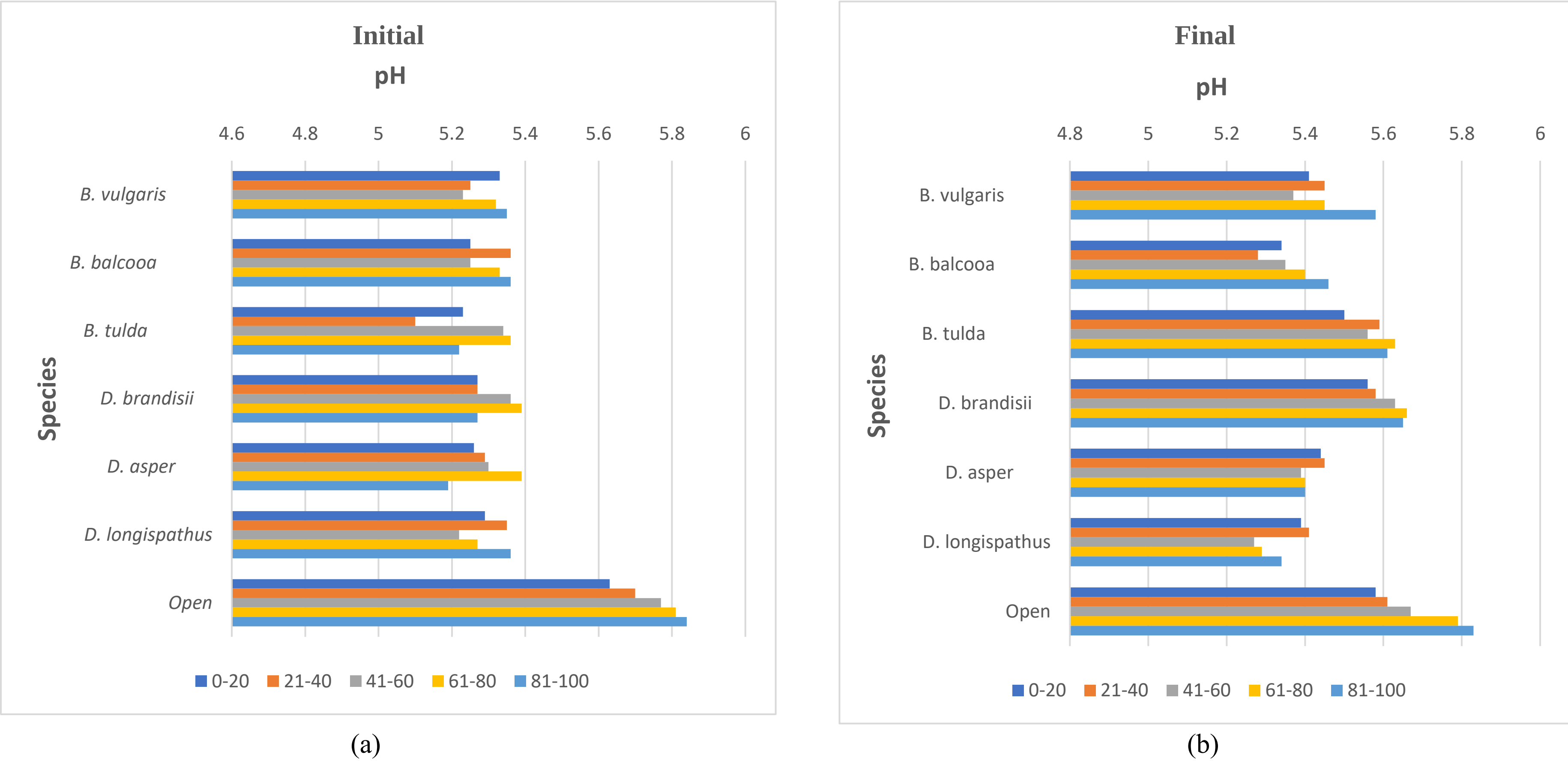


Fig.29. Soil pH under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur a) Initial sampling b) final sampling

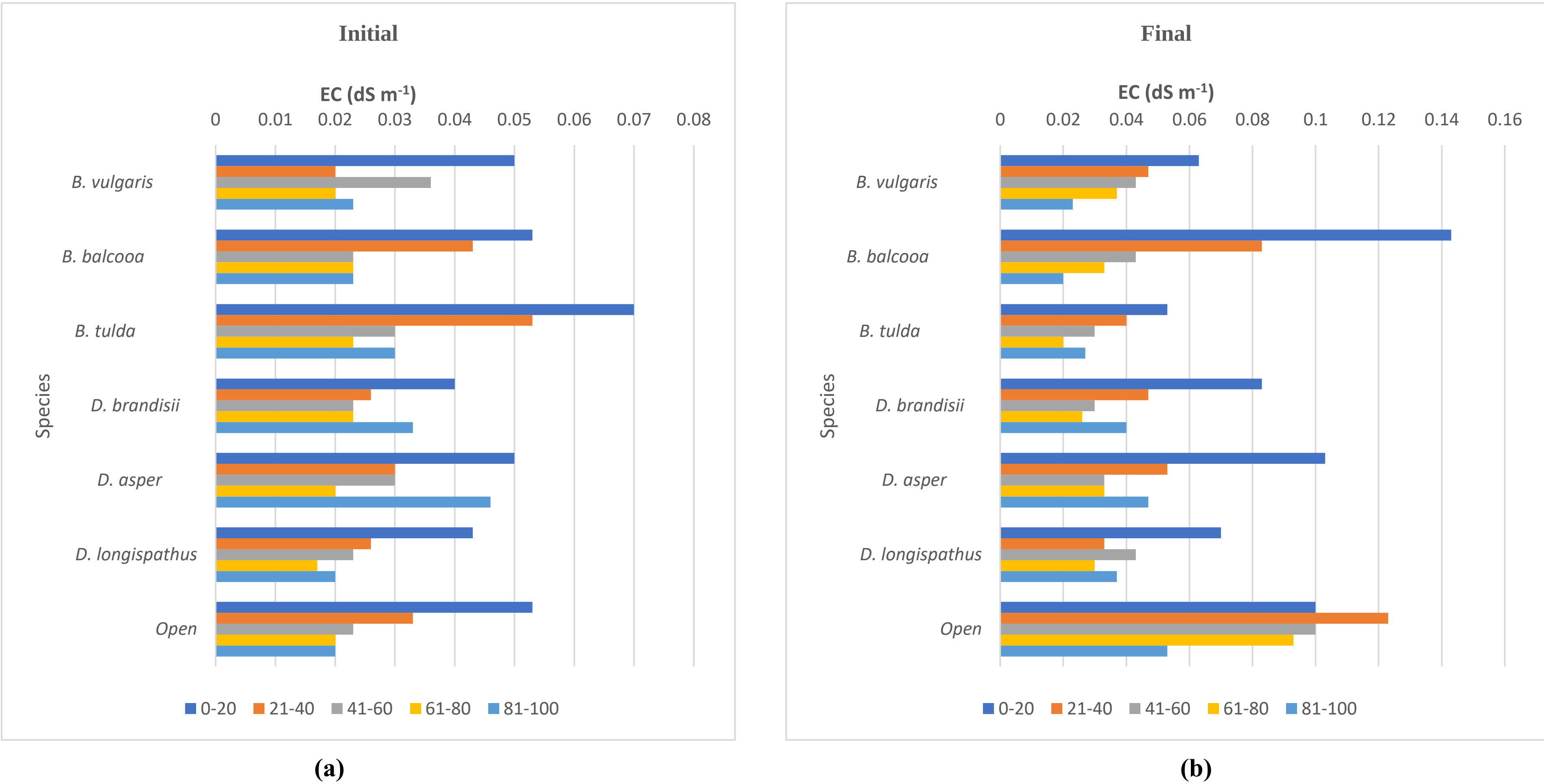


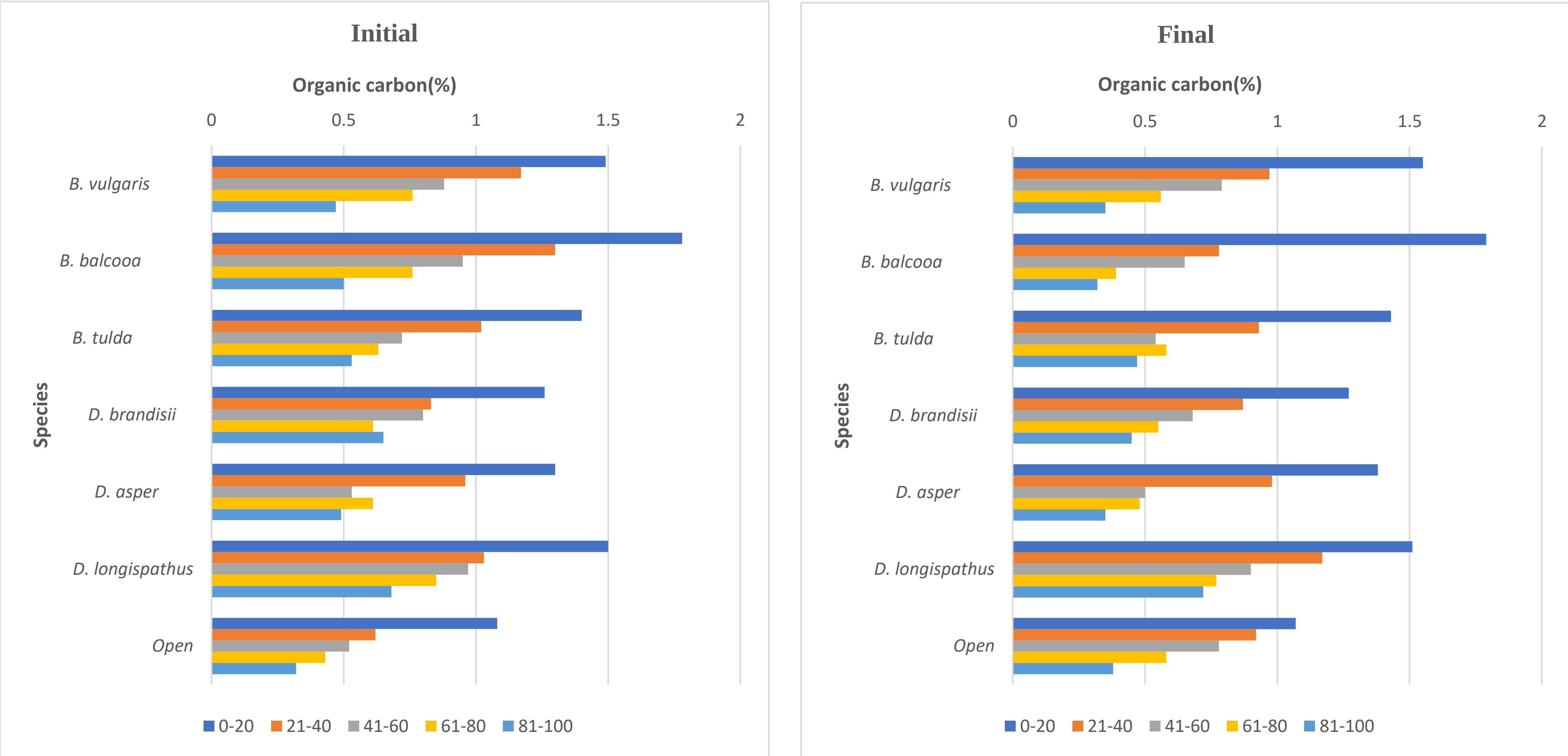
Fig.30. Soil EC (dS m^{-1}) under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur

a) Initial sampling b) final sampling

5.3.6. Soil organic carbon

In present study, the soil organic carbon beneath different bamboo species was significantly higher than that in the adjacent open plot during both sampling periods (Fig.31). This higher organic content under bamboo species might be due to regular deposition of litter and fine root turnover under bamboo plots. Similar results were also observed by Kaushal *et al.,* 2019, where soil organic matter was found to be higher under bamboo plots compared to open plot, they suggested that bamboos have the capacity to enhance soil organic matter by supplying organic material through litter deposition and root residues. The fine roots and root hairs of bamboo plants appear to contribute significantly to both high productivity and increased soil organic carbon levels. Organic carbon also varied among different bamboo species and highest soil organic carbon was reported in *B. balcooa* during both sampling periods. This trend corresponds with the findings of Yourmila, 2017, who also reported higher soil organic carbon beneath *B. balcooa*, this might be attributed to the species' ability to generate better leafy biomass, leading to a greater production of organic matter. Similar results were also observed by Kaushal *et al.,* 2019. Also, the noted differences in organic carbon content among bamboo species were observed by Kaushal *et al.,*2020 and this might be linked to varying amounts of leaf litter, fine roots, and differences in decomposition rates among different bamboo species.

Under present investigation, it was observed that there was a decline in organic carbon content with increasing soil depth, with the highest concentration found in the uppermost layers. This finding aligns with the research conducted by Tamang *et al.,* 2021, who noted elevated organic carbon levels in the surface layer under *Gmelina arborea*. This was attributed to the consistent input of litter, along with moderate levels of temperature and humidity in the study areas. Similar findings were reported by Dey *et al*., 2023.When comparing the initial and final samples, there was a notable increase in organic carbon across all bamboo species and the open plot. This rise in organic carbon was likely be attributed to the higher input of root biomass and litterfall, which tends to increase as bamboo clumps mature, as observed by Nath *et al*., 2015.



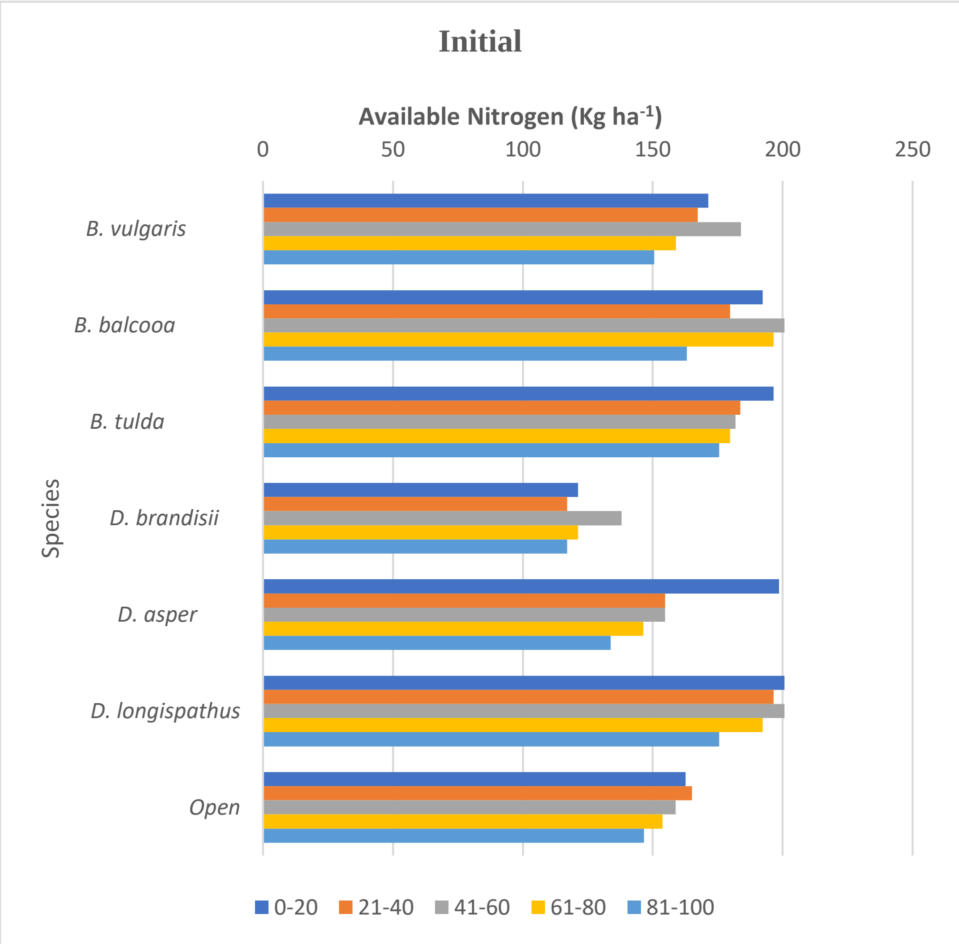
(a) (b)

Fig.31. Soil organic carbon (%) content under selected bamboo species at different depthss during two sampling periods at Vellanikkara, Thrissur a) Initial sampling b) final sampling

5.3.7. Available Nitrogen

In present study, the soil available nitrogen beneath the six bamboo species was significantly higher than that in the adjacent open plot during both sampling periods (Fig.32). However, an exception to this trend was observed in the case of *D. brandisii* where soil available nitrogen was lower than open plot. Lower concentration of available N might be due to higher plant uptake and accumulation of nitrogen in *D. brandisii*. A study by Gaikwad *et al.,*2022(b) reported significantly higher nitrogen uptake (308.3 kg ha^{-1}) by *D. brandisii* as compared to *B. balcooa* (139.5 kg ha^{-1}) and *D. asper* (180.7 kg ha^{-1}). Also, under present study it was observed that among all selected six bamboo species *D. brandisii* had lowest initial nitrogen concentration in decomposing litter (Table 12). This combination of factors, i.e., high nitrogen uptake and limited nitrogen release through litter decomposition, is likely responsible for the comparatively lower levels of available nitrogen found under *D. brandisii*. In contrast, the other bamboo species examined under this study displayed higher levels of available nitrogen compared to the open plot. Similar results were also observed by Kaushal *et al.* 2019, where higher level of available nitrogen was attributed to increased N mineralisation under bamboo soils compared to open soil.

It was also observed that with increasing soil depth available N decreases exception in middle depth (41-60cm) where some increase in available nitrogen was observed compared to its upper layer. This increase in nitrogen availability at the middle depth might be attributed to nitrogen leaching from the surface soil and its accumulation in the middle layer. A similar pattern was observed in a study by Dabi *et al.*, 2021, where the concentration of available nitrogen under selected tree plantations increased in the middle soil layer. When comparing the initial and final samples, there was a slight decrease in available nitrogen across all the bamboo species and the open plot. This trend aligns with findings by Kaushal *et al.*, 2020, where a decrease in nitrogen levels was noted under all selected bamboo species when compared to the initial values. This decline in nitrogen concentration could be attributed to the rapid growth, increased nutrient uptake and storage in the plant biomass, and a reduced return of nutrients to the soil.



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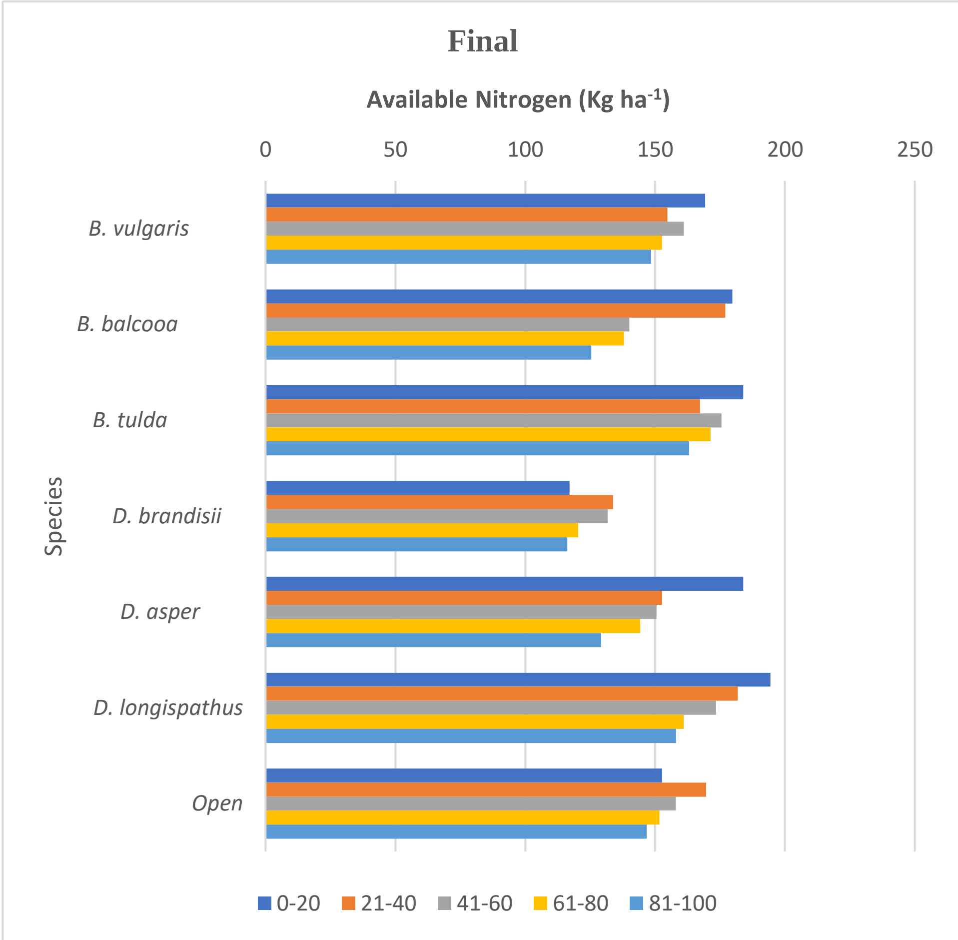
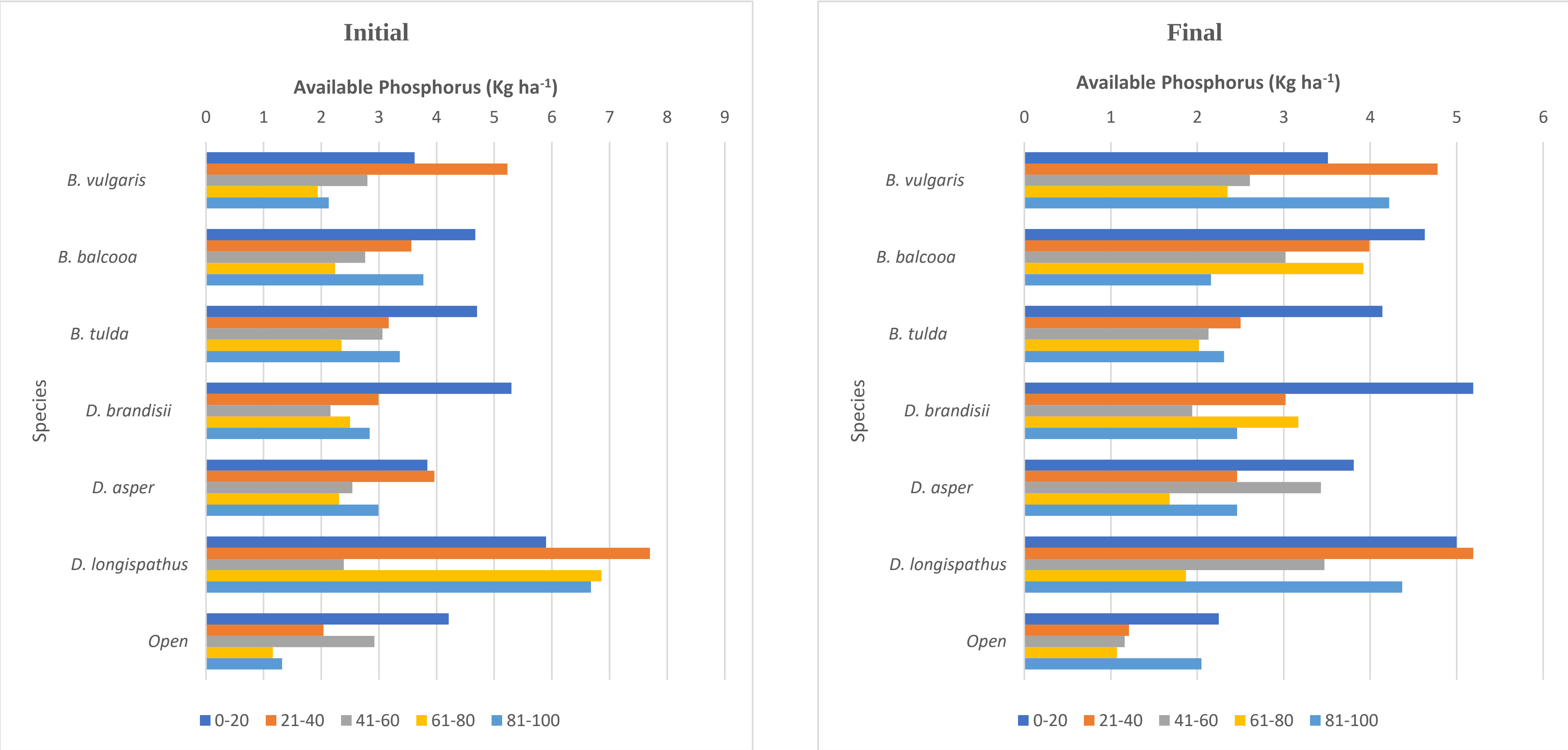


(b)

Fig.32. Available nitrogen (Kg ha^{-1}) content under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur a) Initial sampling b) final sampling

5.3.8. Available Phosphorus

In present study, the soil available P was slightly lower than normal value under all bamboo species (Fig.33). This trend was consistent with the findings of Sujatha (1999), who also observed a similar pattern in *O. travancorica* in Kerala. The reduced availability of phosphorus can likely be attributed to the high intensity of bamboo roots in the surface soil, leading to the extensive uptake of phosphorus released through the decomposition of organic matter. Even in cases where a portion of soluble phosphorus remains unabsorbed, it can readily interact with iron and aluminium in the presence of organic acids, ultimately transforming the available phosphorus into insoluble iron and aluminium phosphate compounds. Similar values of available phosphorus were observed by Tejkaran,2014; and Lakshmy, 2014.In present study *B. vulgaris* and *D. asper* exhibited lower levels of available phosphorus in comparison to the control plot. This decrease in phosphorus content in these species, when compared to their control plots, can likely be attributed to their high phosphorus requirements, as indicated by the high phosphorus content observed in their bamboo shoots (Singh, 2002). Generally, the surface soil displayed a higher concentration of available phosphorus compared to the sub-surface soils, although there were a few exceptions where slightly elevated levels of available phosphorus were recorded in the sub-surface layer. This variability can be attributed to differences in the root patterns of bamboo species, the extraction rate of phosphorus from various soil depths, the leaching characteristics of the soils, and the clay and sesqui-oxide contents in the soils (Venkatesh *et al.,* 2005). In present study available P decreased with increasing depth except for the lowermost layer where observed a slight increase in available phosphorus was observed. This particular anomaly may be influenced by localized factors such as the parent material from which the soil is derived (Shankar, 2022). When comparing the initial and final samples, there was a slight decrease in available phosphorus across all the bamboo species and the open plot. This trend corresponds with the observations made by Kaushal *et al.,* 2020, where a decrease in phosphorus conc. was documented under all selected bamboo species when compared to the initial values. This decline in phosphorus content can be attributed to the high phosphorus uptake and the immobilization of phosphorus in microbial biomass under bamboo. (Singh and Singh, 1999).

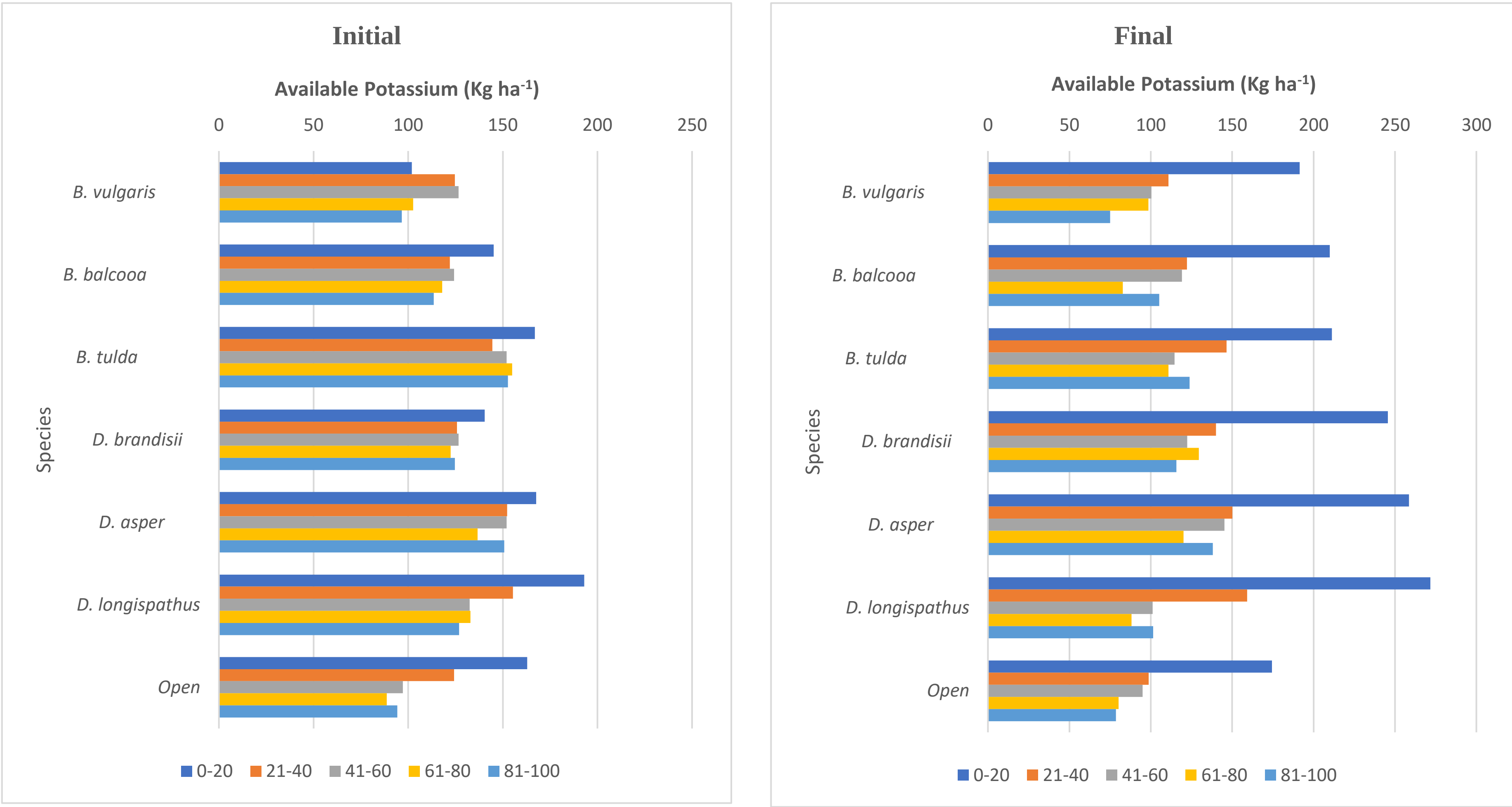


(a) (b)

Fig.33. Available phosphorus (Kg ha^{-1}) content under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur a) Initial sampling b) final sampling

5.3.9. Available Potassium

In present study, the soil available potassium beneath the selected six bamboo species was significantly higher than that in the adjacent open plot (Fig.34). The highest available K was observed under *D. longispathus* during both sampling period. The varying impact of bamboo species on soil available potassium levels may be attributed to differences in potassium uptake by the bamboo species, as well as variations in potassium content and the rate of decomposition of leaf litter (Kaushal *et al.,* 2019). Comparable findings were also reported by Gogoi and Bhuyan (2019). The concentration of potassium exhibited a declining trend with increasing depth, a pattern in line with observations made by Tamang *et al*., 2021, who noted elevated potassium levels in the surface layer beneath *Gmelina arborea*. This was attributed to the consistent input of litter, combined with moderate levels of temperature and humidity in those areas. Similar results were also corroborated by Dey *et al.*, 2023.When comparing the initial and final samples, there was a high increase in available K across all the bamboo species. This surge in potassium concentration can be attributed to the high potassium content found in bamboo leaves, as the current observations indicated that nearly 70% of the potassium was released within the first month of litter decomposition. This rapid release of potassium into the soil suggests that K^+ ions may have been liberated into the soil through the decomposition of the returned biomass. This finding aligns with the results reported by Nath *et al.,* 2015, where they also noted an increase in K^+ content as soil developed under older agroforestry stands, indicating that K^+ ions might have been released into the soil through the decomposition of the organic matter returned to the soil. Similar results were observed by Tariyal *et al.*,2013.

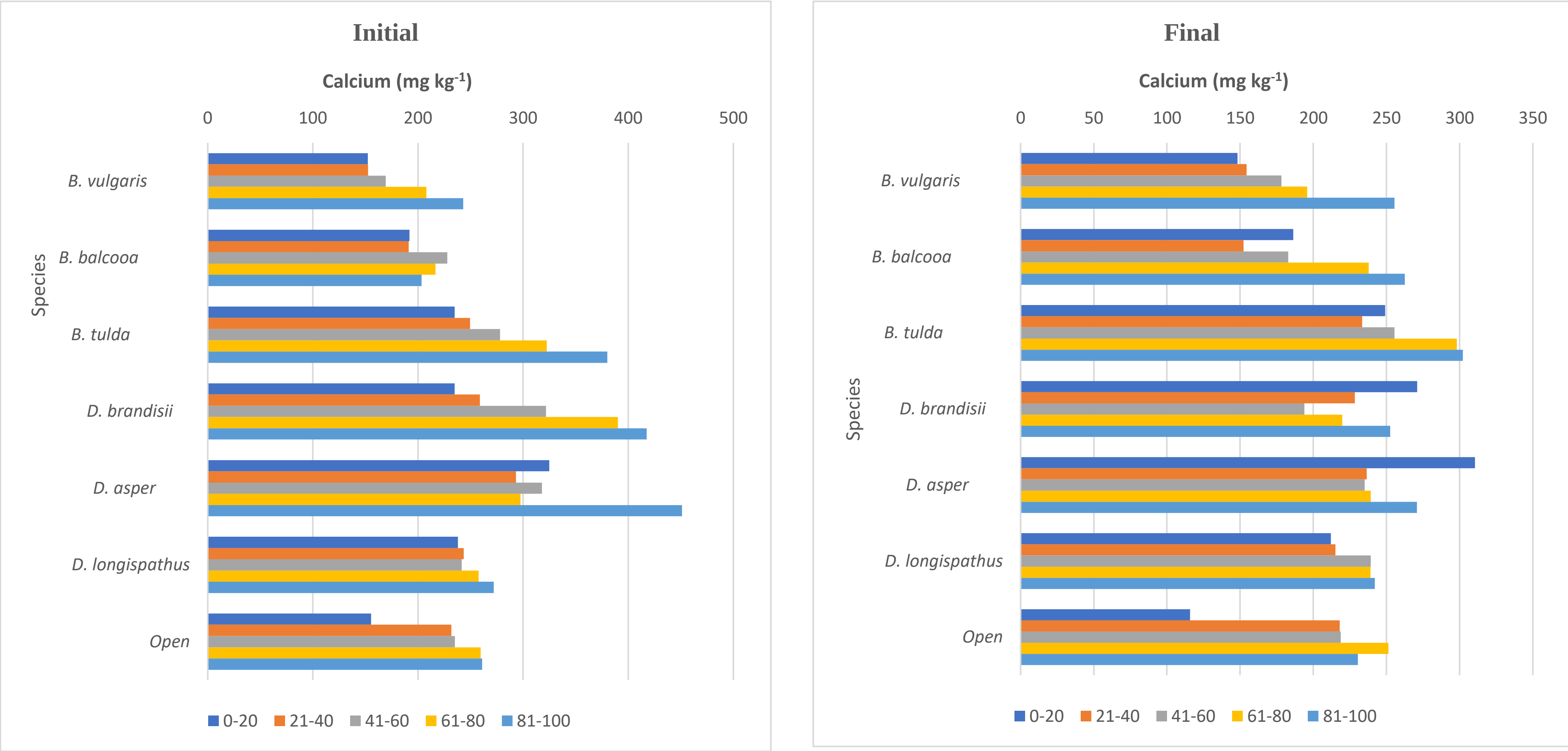


(a) (b)

Fig.34. Available potassium (Kg ha^{-1}) content under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur a) Initial sampling b) final sampling

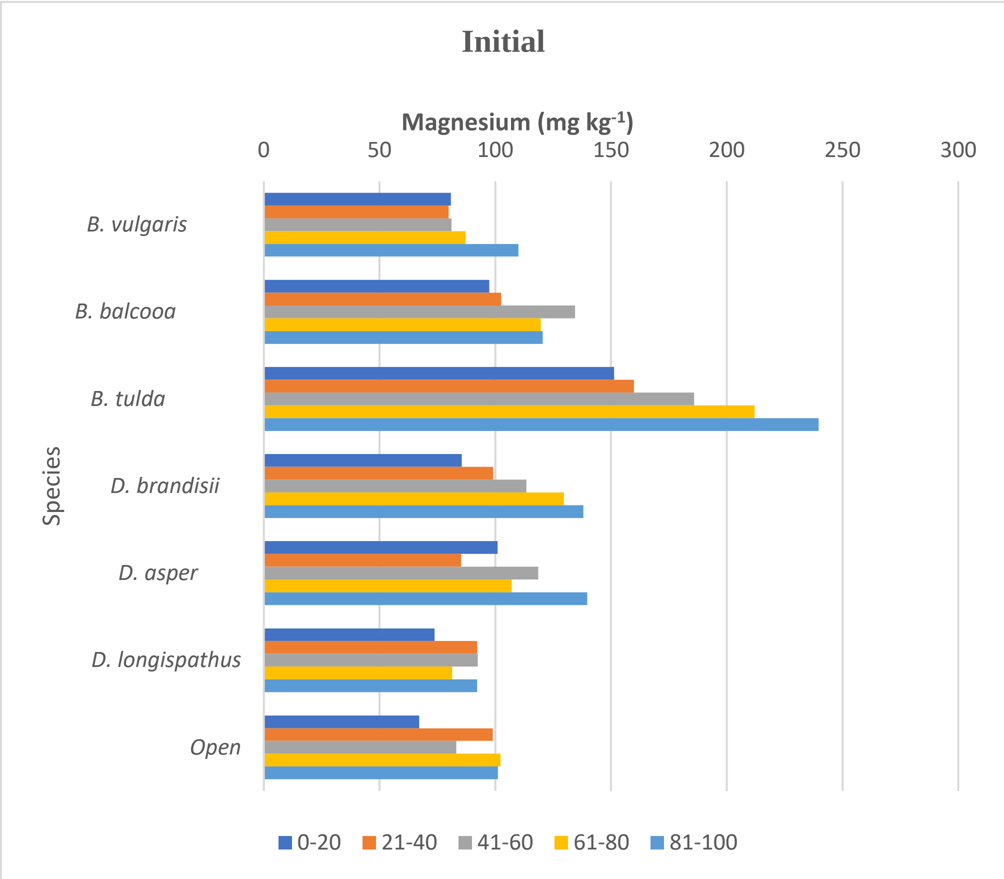
5.3.10. Calcium and Magnesium

In present study, the soil calcium beneath the selected bamboo species was significantly higher than that in the adjacent open plot except in *B. vulgaris* where soil calcium was statistically at par with open plot (Fig. 35). The highest soil calcium content was recorded under *D. asper*. This aligns with the findings of Kumari and Bhardwaj (2017), who also noted the highest levels of exchangeable calcium under *D. asper* in the mid hills of Himachal Pradesh. This might be attributed to the comparatively lower calcium uptake by *D. asper*. Additionally, Pandey and Ojha (2013) observed that the concentration of calcium in *D. asper* shoots decreases as the shoots age. The available calcium under bamboo species was comparatively higher that open plot. This increased calcium content under bamboo, as compared to the open plot, is likely due to the combination of litterfall and subsequent release of calcium under bamboo species (Shanmughavel *et al.*, 2000). While it is commonly believed that calcium content tends to decrease with increasing soil depth, However, in the current study, we observed an opposite trend, with calcium concentration actually increasing with increasing soil depth. This increase in calcium content with depth might be attributed to the presence of higher clay content in lower depths of Vellanikkara soil as calcium is position cation it can be easily leached out with the percolating water and gets deposited in the lower layers where clay content is high. This aligns with the findings of Pereira *et al.*, 2016, who also noted an increase in calcium concentration with soil depth. This increase could be attributed to the leaching and subsequent deposition of calcium in the lower layers. This trend was also observed by Erdem (2022) and Mukshi (2013). Additionally, Panhwar *et al.,* 2016 identified a positive correlation between soil pH and available calcium. In the present study, we observed an increasing trend in pH with increasing soil depth, which may contribute to the rising concentration of calcium at greater depths. When comparing the initial and final samples, there was a slight decrease in available Ca across all the bamboo species. This decrease can be attributed to the faster growth rate and the high uptake of calcium during the early stages of growth, as reported by Kaushal *et al.*, 2020. A similar trend was

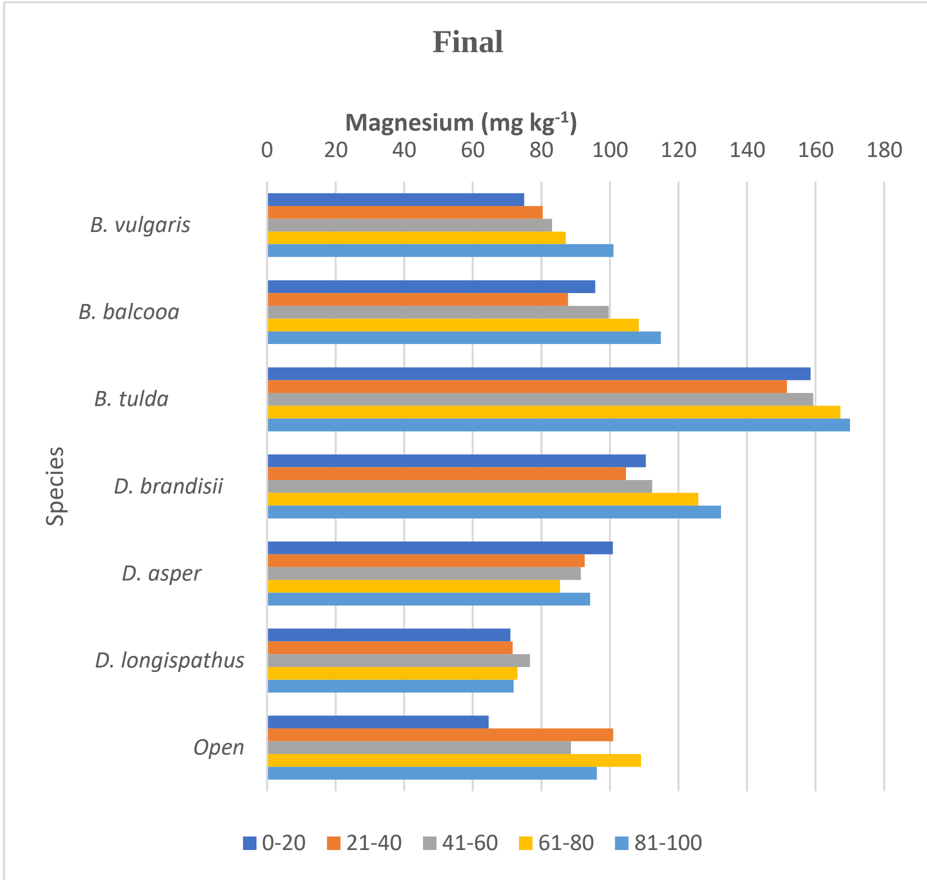


(a) (b)

Fig.35. Calcium content (mg kg^{-1}) content under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur a) Initial sampling b) final sampling



(a)



(b)

Fig.36. Magnesium content (mg kg^{-1}) content under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur a) Initial sampling b) final sampling

observed by Turner and Lambert (1988), where they also documented a decline in soil calcium levels as the plantation aged.

Magnesium exhibited a similar pattern to calcium (Fig.36), as both calcium ions and magnesium ions display analogous behaviour in the soil, as noted by Stinner *et al.*,1984 and Pereira *et al.,* 2016.

5.3.11. Sulphur

In present study, the soil sulphur beneath the selected bamboo species was significantly higher than that in the adjacent open plot (Fig.37) with the exceptions being *B. vulgaris* and *D. brandisii*, where the sulphur content was lower compared to the open plot. This lower sulphur content might be attributed to the high sulphur consumption and accumulation capacity of these particular species. On the other hand, all the other bamboo species exhibited higher sulphur content in comparison to the open plot. This could be due to the litterfall under bamboo species and the subsequent decomposition, as indicated by Kaushal *et al*., 2020. The varying impact of bamboo species on soil available sulphur levels may be linked to differences in sulphur uptake by the bamboo species, as well as variations in nutrient content and the rate of decomposition of leaf litter, as noted by Kaushal *et al.* 2019. In the present investigation, the available sulphur content was slightly lower than the normal value, which may be attributed to the lower pH of the study area. Similar observations were made by Rakesh *et al*., 2020, where they found that available sulphur can decrease by up to 1% of the total sulphur in certain acidic soils.

In the current study, the sulphur content declined with increasing soil depth. This decline can be attributed to the higher input of litter and organic matter in the surface layer compared to the lower depths. The subsequent decomposition of this organic material and the mineralization of nutrients may be responsible for the elevated sulphur content in the surface layer (Noman *et al.,* 2021 and Singh *et al.*, 2019). When comparing the initial and final samples, there was a slight decrease in available sulphur across all the bamboo species. This decrease can be attributed to the faster growth rate and the high uptake of sulphur during the early stages of growth, as reported by Kaushal *et al.*, 2020.

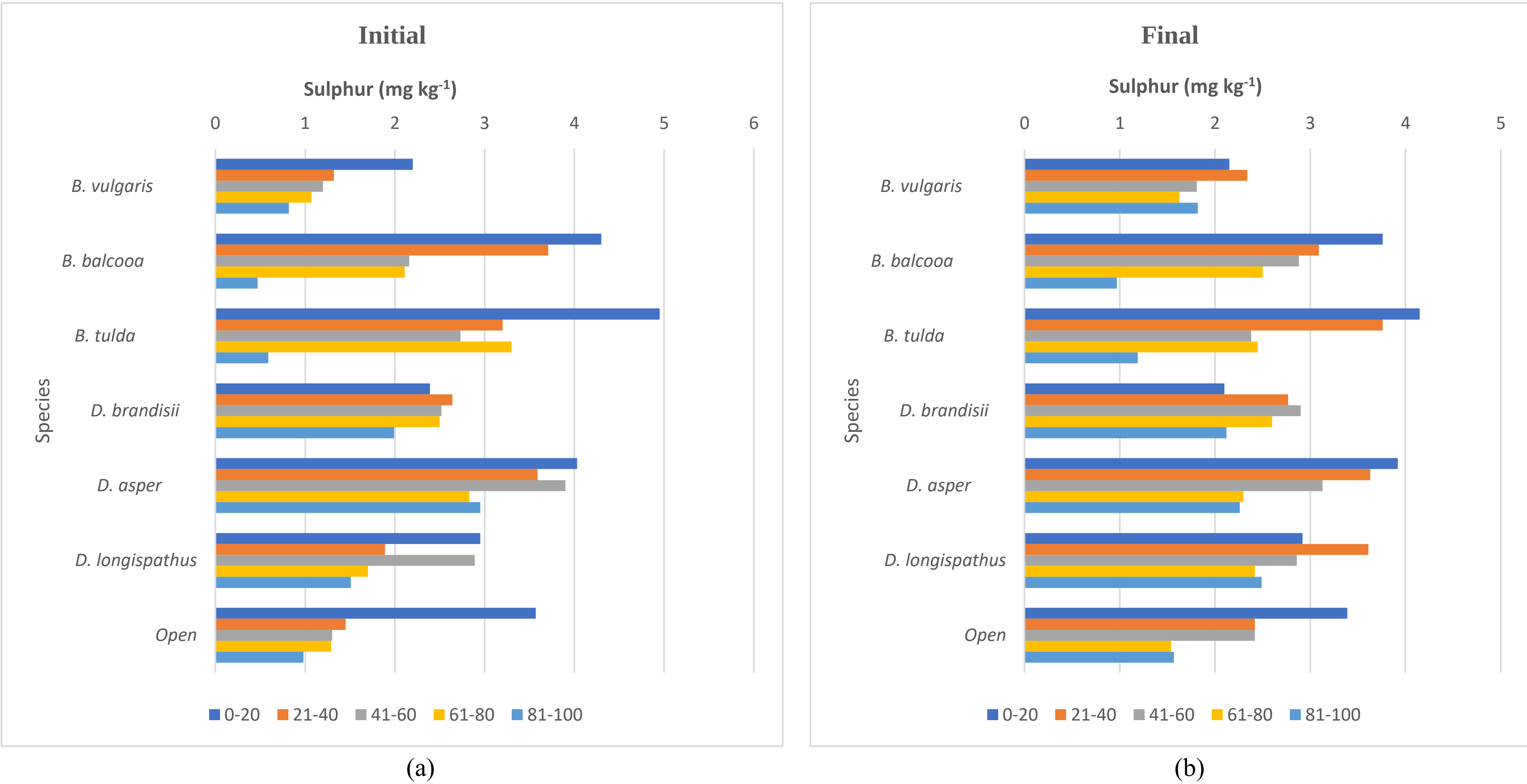


Fig.37. Sulphur content (mg kg^{-1}) content under selected bamboo species at different depths during two sampling periods at Vellanikkara, Thrissur a) Initial sampling b) final sampling

5.4. Soil biological properties

5.4.1. Total microbial count

The microbial population displayed notable variations among different bamboo species. Under present study bacterial population beneath the selected bamboo species was significantly higher than that in the adjacent open plot. This could be attributed to the dense foliage and rapid growth characteristic of bamboo, allowing it to establish a substantial layer of litter. This layer effectively regulates the soil's microclimate and preserves the soil moisture levels, which is vital for sustaining microbial communities (Fuke *et al.,* 2021). Additionally, the secretion of root exudates by bamboo roots contributes to the promotion of microbial growth. Under present study, the highest bacterial population was observed in *D. longispathus*, and it was statistically on par with B. *vulgaris* (Fig.38). This might be due to the high litterfall recorded in the current study under these particular bamboo species (Table 7). Furthermore, it's well-established that different plant species release various organic compounds into their rhizosphere, which could explain the variations in bacterial population among the six bamboo species (Smith, 1969).

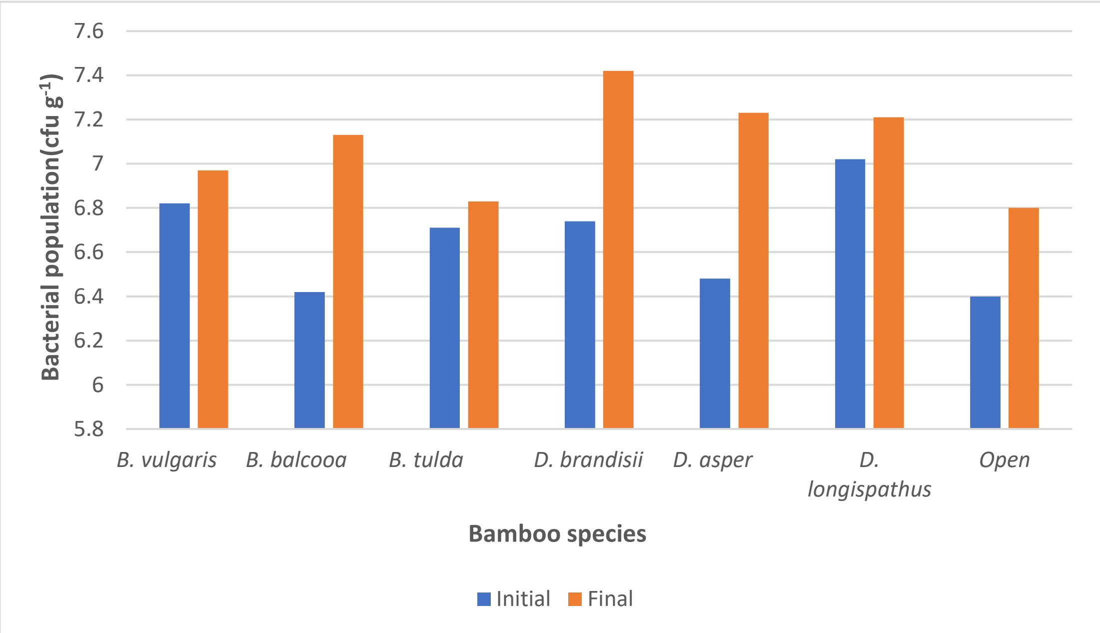


Fig.38. Total bacterial population (cfu g^{-1}) under selected bamboo species during two sampling periods at Vellanikkara, Thrissur

When comparing the initial and final samples, an increase in bacterial population was observed, with the most substantial increase observed under *D. brandisii* (34.9%). The rise in soil bacterial population during the final sampling period can be attributed to several factors. As bamboo plants age, the quality of litter input and the components of root exudates from different species may change, leading to an increase in bacterial counts (Xu *et al.*, 2020). Additionally, during the final sampling period, there was an increase in soil moisture content under all bamboo species due to monsoon showers, which likely contributed to the increase in bacterial populations.

Under present study, the highest actinomycetes population was observed in *B. vulgaris* (Fig.39). This observation is in line with the findings of Mahesh, 1997, who also reported the highest actinomycetes population under *B. vulgaris* (9.30 cfu $\times 10^4$), indicating the preferential influence of bamboo species on the microbial community. The elevated actinomycetes population in *B. vulgaris* can be attributed to the high annual litterfall and high soil organic carbon content observed under this particular species (Table 7 and 22). In the present study, the actinomycetes population varied significantly under different bamboo species, with all of them exhibiting higher actinomycetes populations compared to the open plot. The increased population under different bamboo species is likely due to the presence of root exudates produced by the host plant. This aligns with the observations made by Curl and Truelove (1986), who noted that root exudates enhance nutrient availability indirectly by serving as a carbon substrate, thus promoting microbial growth and activity in the rhizosphere. Variations in the substances exuded by different plant species influence the composition of the rhizosphere microbial population, resulting in microflora specific to each plant (Neal *et al.*, 1973).

When comparing the initial and final samples, there was an increase in the actinomycetes population, and the highest increase was observed under open (7.69%). The rise in actinomycetes populations during the final sampling period can be linked to the onset of the monsoon season and the subsequent increase in soil moisture content. This finding aligns with the observations of Shilpkar *et al.*

(2010), where the highest actinomycetes population was noted during the monsoon season. This may be due to the lower temperatures during the monsoon season, which result in reduced oxidation of organic matter and consequently, an increase in organic carbon content during these seasons compared to the summer.

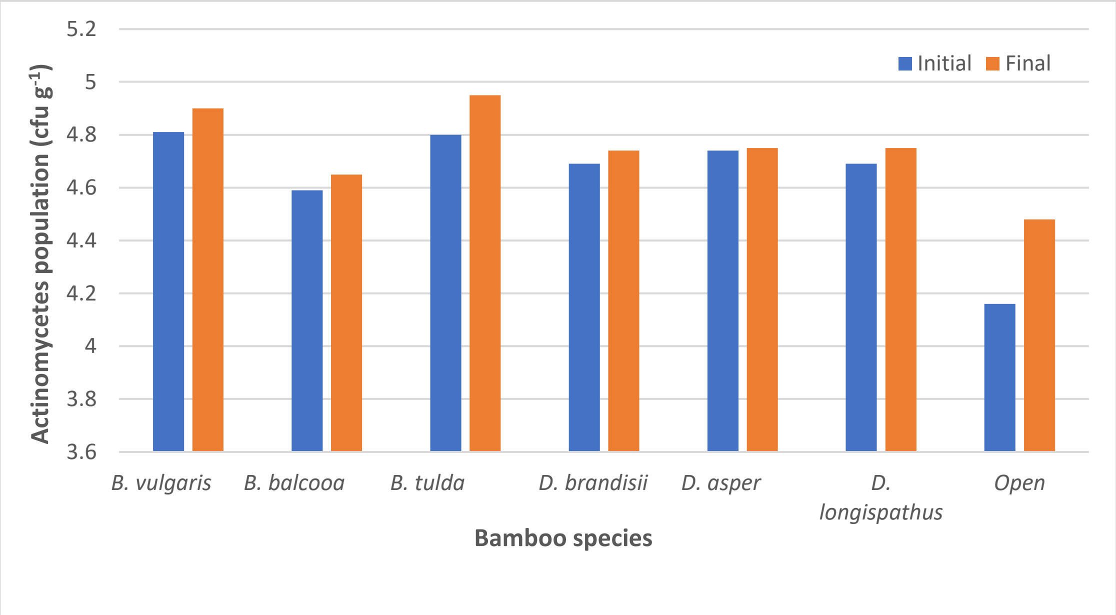


Fig.39. Total actinomycetes population (cfu g^{-1}) under selected bamboo species during two sampling periods at Vellanikkara, Thrissur

Under present study, the highest fungal population was observed in *D. longispathus* which was statistically at par with *B. tulda*, and *B. balcooa* (Fig.40). This could be attributed to the high litterfall, elevated levels of soil organic carbon, and increased soil moisture observed under these bamboo species. Conversely, the lowest fungal population was observed under *B. vulgaris*, and it was statistically at par with open plot. This aligns with the findings of Kaushal *et al.*, 2020, who also noted slightly lower fungal populations under *B. vulgaris* compared to the open plot. Interestingly, *B. vulgaris* exhibited the highest percentage increase (9.20%) in fungal populations during the final sampling compared to the initial sampling, indicating a positive impact of bamboo species on fungal population. In the current study, the fungal population varied significantly under different bamboo species, which can be attributed to differences in the substances exuded by various plant species, affecting the composition of the rhizosphere microbial population and leading to specific microflora associated with each plant species (Neal *et al.,* 1973).

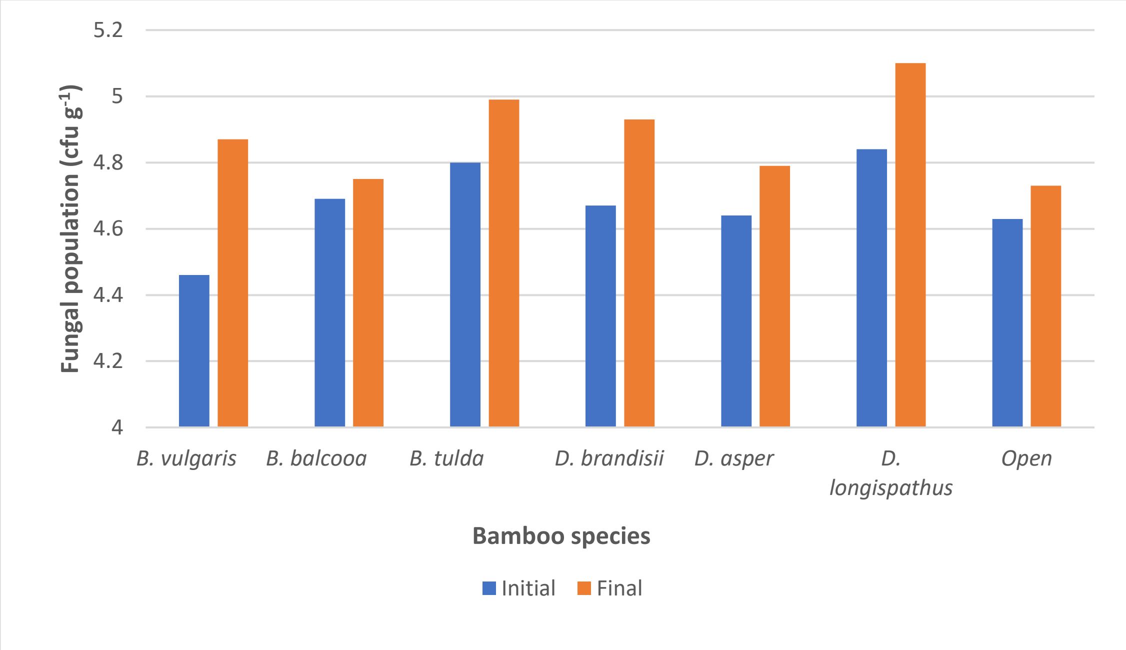


Fig.40. Total fungal population (cfu g^{-1}) under selected bamboo species during two sampling periods at Vellanikkara, Thrissur

When comparing the initial and final samples, an increase in the fungal population was noted under all bamboo species, with *D. longispathus* once again exhibiting a high fungal population. This increase could be attributed to the pre-existing high fungal population under this species. The rise in fungal populations during the final sampling can be linked to the monsoon shower, resulting increase in soil moisture content. This trend aligns with the observations made by Li *et al*. (2022), where they found that the soil fungal community was significantly influenced by soil moisture levels. Similar trends were also observed by Lakshmy (2014).

5.4.2. Dehydrogenase activity

Dehydrogenase activity exhibited significant variations among different bamboo species (Fig.41). In the current study, the dehydrogenase activity beneath the six bamboo species was higher compared to the adjacent open plot. Similar findings were reported by Maini *et al*., 2020, where lower dehydrogenase activity was observed in barren land as opposed to other tree-based land use systems. This difference can be attributed to the addition of organic matter through litter, which stimulates dehydrogenase activity by providing a substrate for the soil microbial community.

Among the different bamboo species, *B. tulda* recorded the highest dehydrogenase activity. The likely reason for this elevated dehydrogenase activity is the higher soil moisture observed under *B. tulda*. Dehydrogenase activity is known to have a positive correlation with soil moisture, as noted by Garg *et al*., 2013. Similarly, Garg *et al.,* 2013 also reported high dehydrogenase activity under *B. tulda* (68.58 µg/25ml/g/24h), although their value was comparatively higher than the one observed in the current study, possibly due to different environmental conditions in the study area. Błońska *et al.* (2021) observed that the components released during litter decomposition stimulate the activity of the dehydrogenase enzyme. In the current study, we observed a high amount of N, P, K in the initial litter samples of *B. tulda* (Table 12). These nutrients likely acted as a nutrient-rich substrate for microbial communities, ultimately enhancing dehydrogenase activity under *B. tulda*.

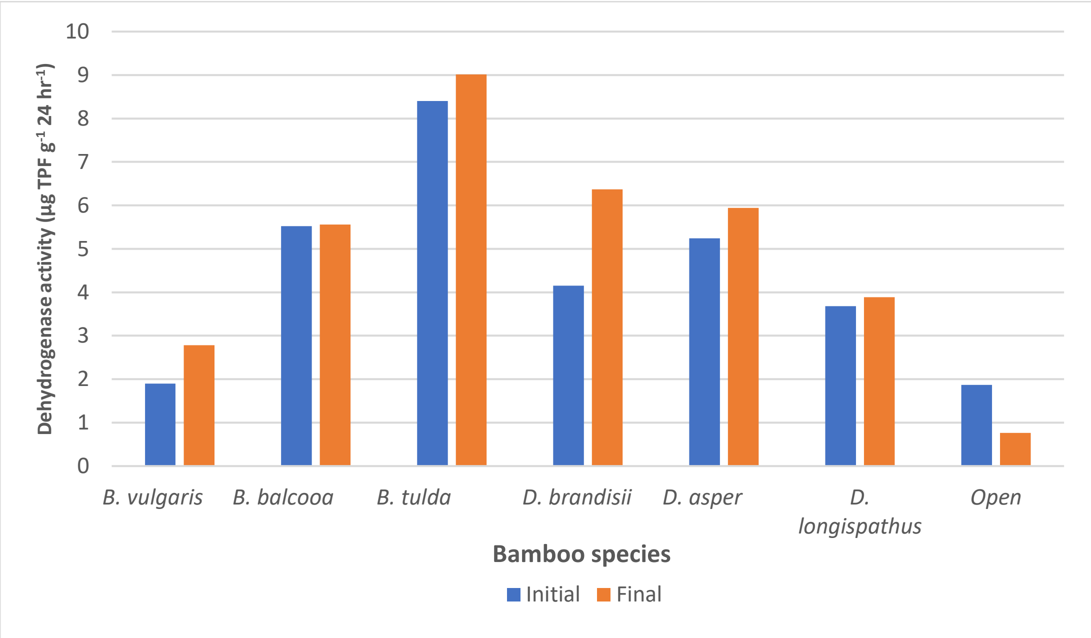


Fig. 41. Dehydrogenase activity (µg TPF g^{-1} 24 hr^{-1}) under selected bamboo species during two sampling periods at Vellanikkara, Thrissur

When comparing the initial and final samples, an increase in the dehydrogenase activity was noted under all bamboo species, with *B. tulda* once again displaying a high level of dehydrogenase activity. This increase could be attributed to the pre-existing high dehydrogenase activity under this species, which might have been further enhanced due to the increased moisture content during the final sampling, resulting from the monsoon shower. The overall rise in dehydrogenase activity during the final sampling under all species can be linked to the influence of the monsoon shower, which led to an increase in soil moisture content. Arshad (2020) also observed the increased dehydrogenase activity under flooded area compared to flooded area. Bandyopadhyay and Maiti (2021) observed a positive correlation between dehydrogenase activity and soil organic carbon. In the current study, it was also noted that soil organic carbon increased during the final sampling, which may be one of the factors contributing to the elevated dehydrogenase activity in the final sampling.

The correlation analysis revealed that the large number of soil variables were corelated with each other (Fig.42). Soil organic carbon exhibited moderate positive correlations with available nitrogen (r=0.35), soil moisture content (r=0.43), total fungal population (r=0.44) and bacterial population (r=0.41). It was negatively correlated with bulk density (r= -0.75). Nanganoa *et al.* (2019) observed a strong significant negative correlation between organic matter and bulk density (r = −0.9653). Uthappa (2021) also reported negative corelation between soil organic carbon and bulk density (r=-0.74). This negative correlation might contribute to the higher soil organic carbon content observed in *B. balcooa*, as this species exhibited the lowest bulk density.

A positive correlation was observed between soil organic carbon and bacterial and fungal populations. Soil organic carbon plays an important role in influencing soil microbial population as most soil microorganisms rely on SOC decomposition to obtain energy (Tian *et al.,* 2021). Many studies have highlighted a positive correlation between SOC and soil bacterial and fungal populations (Tan *et al.,* 2019: Tian *et al.,* 2021: Kallenbach *et al.,* 2016).

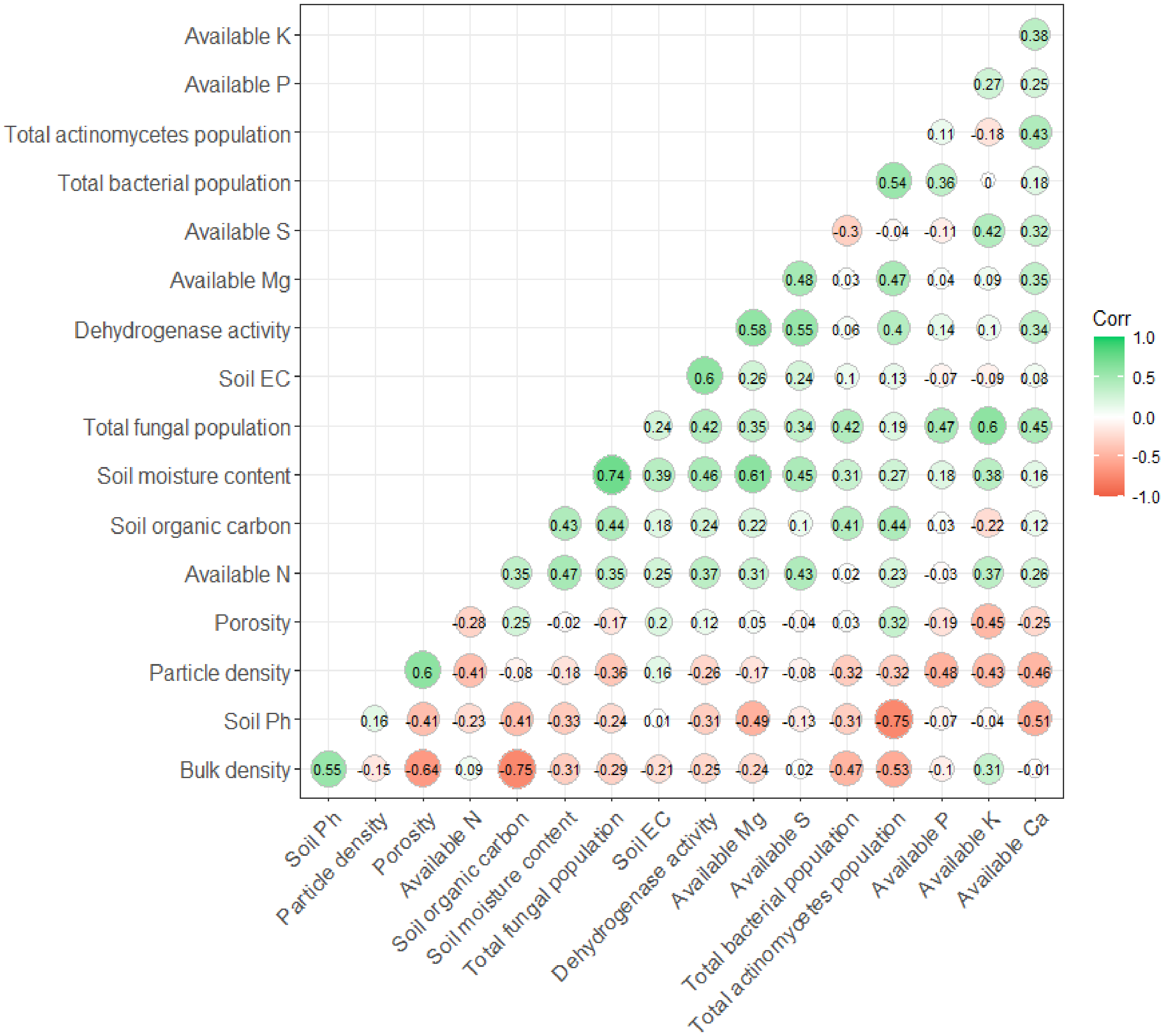


Fig. 42 Correlation analysis between soil physicochemical and biological properties at Vellanikkara, Thrissur

Furthermore, available nitrogen showed a moderately positive correlation with soil organic carbon. This aligns with the findings of Wibowo and Kasno (2021), who reported a positive correlation between soil organic carbon and soil available nitrogen (r=0.84). This correlation is attributed to the influence of soil organic carbon on soil microbial populations, with these microorganisms playing a crucial role in nitrogen mineralization (Wu *et al.*, 2022).

The soil fungal population displayed a positive correlation with both soil moisture content (r=0.74) and dehydrogenase activity (r=0.42). Tiwari *et al*. (1987) observed a similar positive correlation of soil moisture content with soil fungal population, attributing it to increased moisture bringing more soluble organic matter into solution, thereby fostering an environment conducive to an increased fungal population. Additionally, Jha *et al*. (1992) noted a positive correlation between fungal population and dehydrogenase activity.

Furthermore, a moderate positive correlation was observed between dehydrogenase activity (r=0.46) and soil moisture content. Soil moisture content strongly influences soil microbial activity, community composition, and consequently, soil enzymatic activities (Geisseler *et al*., 2011). In the wet soils, the higher moisture content can solubilize organic matter, potentially contributing to an increase in microbial population (Subhani *et al.*, 2001). Gu *et al.* (2009) also reported elevated dehydrogenase activity in flooded soils compared to non-flooded conditions, indicating a significant impact of soil moisture on dehydrogenase activity.

Summary

6 SUMMARY

The research work entitled "Litter dynamics and soil changes under six-year-old bamboo stands" was undertaken at bambusetum, College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur during 2022-2023 with the main objectives to quantify the litter and nutrient turnover and changes in the physicochemical and biological properties of soil under six bamboo species viz. *Bambusa vulgaris Schrad*, *Bambusa balcooa Roxb., Bambusa tulda Roxb., Dendrocalamus brandisii* (Munro) Kurz.*, Dendrocalamus asper* (Schult.f.) Back.ex Heyne and *Dendrocalamus longispathus* Kurz.

The salient findings of research are summarized below:

6.1. Growth performance of selected bamboo species

1. Among the six bamboo species studied, Dendrocalamus *brandisii* (14.95m) recorded the highest clump height followed by *Dendrocalamus asper* (14.27m) while the lowest clump height was recorded for *Bambusa tulda* (10.45m). Under the period of observation maximum increase in clump height was displayed by *Dendrocalamus asper* (18.42%).
2. Average culm girth was recorded highest in *Bambusa vulgaris* (22.71cm) while the lowest value was observed in *Bambusa tulda* (13.58 cm). Under the period of observation maximum increase in culm girth was displayed by *Dendrocalamus brandisii* (10.83%).
3. The maximum number of culms per clump was observed in *Dendrocalamus asper* (56.25) followed by *Bambusa tulda* (49.50) while the lowest number of culms per clump was recorded under *Bambusa balcooa* (17.50). However, the increase in the number of culms per clump were observed during the study period with maximum increase was noted in *Dendrocalamus brandisii* (10.43%).
4. Average clump circumference was recorded highest in *Bambusa vulgaris* (6.47m) and lowest value was recorded in *Dendrocalamus brandisii* (5.01m). During all observation periods marginal increase were observed in

clump circumference with maximum increase was noted in *Bambusa balcooa*.

5. Average internodal length was recorded highest for *Dendrocalamus brandisii* (44.01 cm) while lowest internodal length was recorded in *Bambusa tulda* (19.66cm). During the four periodic measurements increase in internodal length were observed for all species and highest rate of internodal length was observed in *Dendrocalamus asper* (4.75%).

6.2. Litter dynamics

1. Distinct seasonal variation in litter production among six selected bamboo species were visible in the present study. Annual litter production in selected bamboo species varied from 9.64-6.98Mg ha^{-1} $year^{-1}$. Highest annual litter production was observed under *Bambusa vulgaris* (9.64 Mg ha^{-1} $year^{-1}$) while lowest annual litter production was observed under *Bambusa balcooa* (6.98 Mg ha^{-1} $year^{-1}$).
2. Bimodal patter of litter production was observed except in *Bambusa balcooa* (trimodal). The major peak in litterfall was observed during the winter season (December to January) while minor peak observed in June or July. Profound seasonal variation in litterfall was observed.
3. The overall composition of litter was primarily characterized by leaf litter, constituting over 70% of the total litterfall in all bamboo species. Twigs accounted for more than 16% of the total litterfall, while the lowest contribution was attributed to sheath litter. The quantity of different litter fractions was in the order: leaves > twigs > sheath.
4. Mass remaining (%) during litter decomposition also varied significantly between species and months. In present study three phase decomposition pattern (consisting of an initial faster phase, followed by an intermediate slower phase, and concluding with a terminal fast phase) was observed for all the bamboo species.
5. The decomposition study revealed that the mass loss in litter samples followed a negative exponential pattern. Notably, species with a high initial N concentration, such as *Bambusa tulda*, exhibited rapid decomposition

rates. Conversely, *Bambusa balcooa*, despite having relatively high nitrogen content, showed slower decomposition rates.

6. At the end of decomposition study, the average litter remaining in the litter bags were 12.20%, 16.35%, 0.6%,14.65%, 9.4and 14.45% for *Bambusa vulgaris, Bambusa balcooa, Bambusa tulda, Dendrocalamus brandisii, Dendrocalamus asper, Dendrocalamus longispathus* respectively. The decay rate coefficient also showed variation among the bamboo species. Highest decay rate coefficient was recorded in *Bambusa tulda* (0.292 month $^{-1}$) while *Bambusa balcooa* (0.123 month $^{-1}$) recorded the lowest rate.
7. Generally, a triphasic pattern (initial loss, immobilization, and eventual release) of N, P, K release was observed under the bamboo species with exception in *B. vulgaris, B. balcooa,* and *D. longispathus*, where initial immobilization of phosphorus concentration was observed.

6.3. Physico chemical properties of soil under selected bamboo species

1. During both the sampling periods, soil bulk density was recorded maximum under open plot and minimum under and lowest under *Bambusa balcooa*. Further increasing trend in bulk density with increase in soil depth was noticed in all bamboo species.
2. During both sampling period soil particle density was recorded maximum under open plot and minimum under and lowest under *Dendrocalamus longispathus*. Further increasing trend with increase in soil depth was noticed in all bamboo species.
3. At surface soil, highest soil porosity was found under *Bambusa balcooa* and lowest under open plot during both sampling period. Further decreasing trend with increasing depth was found in all species. The higher soil moisture was recorded in *Bambusa tulda* during both sampling period, while lowest under *Bambusa vulgaris* (Initial) and open plot during final sampling period. Further the soil moisture showed an increasing trend with depth. All the bamboo species recorded higher soil porosity as compared to the open plot.

4. Soil pH and EC has showed an inverse relationship. High soil pH was observed under open plot and lowest under *Bambusa tulda*(initial) and *Bambusa balcooa* during the final sampling. Further increasing trend with increasing soil depth was found. High soil EC was found under *Bambusa tulda*(initial) and *Bambusa balcooa*(final) and lowest under *Dendrocalamus brandisii*(initial) and *Bambusa tulda* during final sampling period.
5. At surface soli, *Bambusa balcooa* recorded highest soil organic carbon 1.78%(initial) and 1.79%(final) and lowest in open plot 1.08% (initial) and 1.07%(final). A decreasing trend in organic carbon with increasing soil depth was noticed under all bamboo species. All bamboo species recorded higher organic matter content as compared to the open plot.
6. The highest levels of available N, P, and K were found under *Dendrocalamus longispathus*, both initially (200.70 Kg ha^{-1}N, 5.90 Kg ha^{-1}P, 193.92 Kg ha^{-1} K) and at the final sampling period (194.43 Kg ha^{-1}N, 5.00 Kg ha-1P, 271.78 Kg ha^{-1} K).Conversely, the lowest available N was recorded under *Dendrocalamus brandisii*, with 121.26 Kg ha^{-1} initially and 117.08 Kg ha^{-1} at the final sampling. For phosphorus and potassium, the lowest levels were observed under *Bambusa vulgaris*, with 3.62 Kg ha^{-1}P and 101.92 Kg ha^{-1}K initially, and 3.51 Kg ha^{-1}P at the final sampling. The lowest available potassium during the final sampling was observed in the open plot, with 174.46 Kg ha^{-1}. Further, available potassium exhibited a decreasing trend with increasing depth. However, available nitrogen and phosphorus did not show a consistent decreasing trend with increasing depth.
7. At topsoil, *Dendrocalamus asper* (initial: 324 mg kg^{-1}, final:310 mg kg^{-1}) recorded the highest soil calcium and lowest was recorded under *Bambusa vulgaris* (152.29 mg kg^{-1}) which was statistically at par with open plot during initial sampling, while lowest value during final sampling was observed under open plot (115.80 mg kg^{-1}). further soil calcium showed increasing content with increasing depth.

8. At topsoil, *Bambusa tulda* (initial: 151.29 mg kg^{-1}, final:158.54 mg kg^{-1}) recorded the highest soil magnesium and lowest was observed under open plot (Initial:67.08 mg kg^{-1}, final:64.62 mg kg^{-1}). further soil magnesium showed increasing trend with increasing depth.
9. At topsoil, *Bambusa tulda* (initial: 4,95 mg kg^{-1}, final:4.15 mg kg^{-1}) recorded the highest soil sulphur and lowest was observed under Bambusa vulgaris (2.20 mg kg^{-1}) during initial sampling and *Dendrocalamus brandisii* (2.10 mg kg^{-1}) during final sampling. further soil sulphur showed decreasing trend with increasing depth.

6.4. Soil biological properties under different bamboo species

1. Among six selected bamboo species *Dendrocalamus longispathus* recorded the highest microbial population and lowest in open plot. During the initial sampling, *Dendrocalamus longispathus* exhibited the highest bacterial population (11.00 x 10^{6} cfu g^{-1}), while the open plot had the lowest bacterial population (2.50 x 10^{6} cfu g^{-1}). In contrast, during the final sampling, the bacterial population was highest under *Dendrocalamus brandisii* (26.50 x 10^{6} cfu g^{-1}), while the open plot had the lowest bacterial population (6.50 x 10^{6} cfu g^{-1}). All bamboo species exhibited higher bacterial population compared to open plot during both sampling periods.
2. Among six selected bamboo species, *Bambusa vulgaris* (Initial: 6.50× 10^{4} cfu g^{-1}, final: 8.00× 10^{4} cfu g^{-1}) recorded the maximum actinomycetes population and lowest in open plot (initial:1.50× 10^{4} cfu g^{-1}, final: 3.00× 10^{4} cfu g^{-1}) during both initial and final sampling. All bamboo species exhibited higher actinomycetes population compared to open plot during both sampling periods.
3. Fungal population was recorded highest in *Dendrocalamus longispathus* (initial: 7.00× 10^{4} cfu g^{-1}), final: 12.5× 10^{4} cfu g^{-1}) during both samplings and lowest in *Bambusa vulgaris* (3.00× 10^{4} cfu g^{-1}) during initial sampling and open plot (5.5× 10^{4} cfu g^{-1}) during final sampling. All bamboo species exhibited higher fungal population compared to open plot except *Bambusa*

vulgaris where slightly lower fungal population was recorded only during initial sampling.

4. Dehydrogenase activity recorded highest under *Bambusa tulda* (initial: 8.40 µg TPF g^{-1} 24 hr^{-1}, final: 9.01 µg TPF g^{-1} 24 hr^{-1}) and lowest under open plot (initial: 1.87 µg TPF g^{-1} 24 hr^{-1}, final: 0.76 µg TPF g^{-1} 24 hr^{-1}). All bamboo species exhibited higher dehydrogenase activity compared to open plot during both sampling period.
5. Soil organic carbon exhibited moderate positive correlations with available nitrogen (r=0.35), soil moisture content (r=0.43), total fungal population (r=0.44) and bacterial population (r=0.41) and it was negatively correlated with bulk density (r= -0.75). The soil fungal population displayed a positive correlation with both soil moisture content (r=0.74) and dehydrogenase activity (r=0.42). A moderate positive correlation was also observed between dehydrogenase activity (r=0.46) and soil moisture content.

References

REFERENCES

Abdul Khalil, H. P. S., Bhat, I. U. H., Jawaid, M., Zaidon, A., Hermawan, D., and Hadi, Y. S. 2012. Bamboo fibre reinforced biocomposites: A review. *Mater. & Des.* 42: 353–368.

Ahmad, Z., Upadhyay, A., Ding, Y., Emamverdian, A., and Shahzad, A., 2021. Bamboo: Origin, habitat, distributions and global prospective. In: Ahmad, Z., Ding, Y., Shahzad, A. (eds), *Biotechnological Advances in Bamboo.* Springer, Singapore, pp.1-31.

Akinlabi, E. T., Anane-Fenin, K., and Akwada, D. R. 2017. Bamboo Taxonomy and Distribution Across the Globe. In: Akinlabi, E. T., Anane-Fenin, K., and Akwada, D. R.(eds), *Bamboo*. Springer Cham, pp.1–37.

Akoto, D.S., Partey, S.T., Abugre, S., Akoto, S., Denich, M., Borgemeister, C. and Schmitt, C.B. 2022. Comparative analysis of leaf litter decomposition and nutrient release patterns of bamboo and traditional species in agroforestry system in Ghana. *Cleaner Mater.* 4: 100068.

Akoto, D.S., Partey, S.T., Denich, M., Kwaku, M., Borgemeister, C., and Schmitt, C.B. 2020. Towards bamboo agroforestry development in Ghana: evaluation of crop performance, soil properties and economic benefit. *Agrofor. Syst.* 94: 1759-1780.

Alemayehu, A., Mulatu, Y., Eshete, N., and Terefe, M. 2015. Growth performance and biomass accumulation of four different introduced bamboo species in South-Western Ethiopia. *Growth* 5(3): 5.

Amada, S. and Untao, S. 2001. Fracture properties of bamboo. *Composites Part B: Eng.* 32(5): 451-459.

Amani, K.A., Kunhamu, T.K., Jijeesh, C.M., Niyas, P., Santhoshkumar, A.V. and Anjana, C.B. 2022. Growth performance of selected bamboo species suitable for humid tropics of Kerala, India. *J. of Bamboo & Rattan* 21(1): 1-7.

Amlani, M.H., Tandel, M.B., Prajapati, V.M., Pathak, J.G. and Behera, L.K. 2017. Assessment of growth variation among different species of Bamboo. *Int. J. of Chemical Stud.* 5(6): 1436-1439.

Anderson, J.M. 1988. Spatio-temporal effects of invertebrates on soil processes. *Biol. Fertil. Soils* 6:216–227.

Arshad, A. 2020. Soil and vegetation characteristics in the post flood scenario in selected tree-based land use systems in Thrissur, Kerala. MSc. (For) thesis, Kerala Agricultural University, Thrissur, 70p.

Awasthi, P., Bargali, K., Bargali, S.S. and Khatri, K. 2022. Nutrient return through decomposing Coriaria nepalensis litter in degraded hills of Kumaun Himalaya, India. *Front. For. Glob. Change* 5: 1008939.

Bai, F., Qi, X., Li, P., Du, Z. and Guo, W. 2023. Groundwater Depth and Nitrogen Application Amount Jointly Regulate the Water and Residual Soil Nitrate Accumulation in Agricultural Soil Profile. *Agronomy* 13(4): 1163.

Bandyopadhyay, S. and Maiti, S.K. 2021. Different soil factors influencing dehydrogenase activity in mine degraded lands—state-of-art review. *Water, Air, & Soil Pollut*. 232(9): 360.

Benton, A. 2015. Priority species of bamboo. In: Liese, W. and Köhl, M. (eds), *Bamboo: the plant and its uses*. Springer, Singapore, pp.31-41.

Berg, B. and Laskowski, R. 2006. Litter decomposition: A guide to carbon and nutrient turnover. *Adv. Ecol. Res.*38:448.

Berg, B., Staaf, H. and Wessen, B. 1987. Decomposition and nutrient release in needle litter from nitrogen-fertilized Scots pine (Pinus sylvestris) stands. *Scand. J. For. Res.* 2: 399–415.

Bhardwaj, S.D., Panwar, P. and Gautam, S., 2001. Biomass production potential and nutrient dynamics of Populus deltoides under high density plantations. *Indian For*. 127(2): 144-153.

Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., and Clarck, F.E. 1965. *Methods of soil analysis.* Part 1. Physical properties. American Society of Agronomy. Inc. Publication, Madison, USA, 1569p.

Błońska, E., Piaszczyk, W., Staszel, K. and Lasota, J. 2021. Enzymatic activity of soils and soil organic matter stabilization as an effect of components released from the decomposition of litter. *Appl. Soil Ecol.* 157: 103723.

Bockheim, J.G., Jepsen, E.A., and Heisey, D.M. 1991. Nutrient dynamics in decomposing leaf litter of four tree species on a sandy soil in northwestern Wisconsin. *Can. J. For. Res.* 21(6): 803-812.

Bocock, K.L. and Gilbert, O.J.W. 1957. The disappearance of leaf litter under different woodland conditions. *Plant and Soil* 9(2): 179-185.

Branco, L., Lacerda, C.F.D., Marinho, A.B., de Sousa, C.H., Calvet, A.S., and Oliveira, E.G.D. 2020. Production of Bambusa vulgaris seedlings from rhizomes under brackish water irrigation. *Brazilian J. Agric. and Environ. Eng.* 24:337-342.

Bray, R.H. and Kurtz, L.T. 1945. Determination of total, organic, and available forms of phosphorus in soils. *Soil Sci.* 59(1): 39-46.

Canavan, S., Richardson, D.M., Visser, V., Le Roux, J.J., Vorontsova, M.S., and Wilson, J.R. 2017. The global distribution of bamboos: assessing correlates of introduction and invasion. *AoB Plants* 9(1): 078.

Casida, J.R., Klein, D.A., and Santoro, T. 1964. Soil dehydrogenase activity. *Soil Sci*. 98(6): 371-376.

Chakravarty, S., Rai, P., Vineeta, P.N., and Shukla, G. 2020. Litter production and decomposition in tropical forest. In: Bhadouria, R., Tripathi, S., Srivastava, P., and Singh, P.(eds), *Handbook of Research on the Conservation and Restoration of Tropical Dry Forests.* IGI Global, Hershey PA, USA, pp. 193–212.

Chesnin, L. and Yien, C.H. 1951. Turbidimetric determination of available sulfates. *Soil Sci. Soc. Am. J.* 15(C): 149-151.

Christanty, L., Mailly, D. and Kimmins, J.P. 1996. “Without bamboo, the land dies”: biomass, litterfall, and soil organic matter dynamics of a Javanese bamboo talun-kebun system. *For. Ecol. and Manag.* 87(1-3): 75-88.

Clark, L.G., Londoño, X., and Ruiz-Sanchez, E. 2015. Bamboo Taxonomy and Habitat. In: Liese, W. and Köhl, M. (eds), *Bamboo: the plant and its uses.* Springer, Singapore, pp.1-30.

Coleman DC. and Crossley, D.A. 1996. *Fundamental of Soil Ecology.* New York: Academic Press,205p.

Coleman, D.C., Blair, J.M., Eliott, E.T., and Freckman, D.W. 1999. Soil invertebrates. In: Sollins, P., Robertson, G.P., Bledsoe, C.S., and Coleman, D.C. (eds), *Standard soil methods for long-term ecological research*. Oxford University Press, New York, pp 349–377.

Cornelissen, J.H.C. 1996. An experimental comparison of leaf decomposition rates in a wide range of temperate plant species and types. *J. Ecol*.84: 573–582.

Couˆteaux, M. M., Bottner, P., and Berg, B. 1995. Litter decomposition, climate and liter quality. *Trends in Ecol. Evol.*10(2): 63–66.

Cuevas, E. and Medina, E. 1986. Nutrient dynamics within Amazonian forests: part 1, nutrient flux in fine litter fall and efficiency of nutrient utilization. *Oecologia* 68(3):466–472.

Cuevas, E. and Medina, E. 1988. Nutrient dynamics within Amazonian forests - II. Fine root growth, nutrient availability and leaf litter decomposition. *Oecologia* 76(2): 222–235.

Curl, E.A. and Truelove, B. 1986. Rhizosphere populations. *The Rhizosphere* 93-139.

Dabi, H., Bordoloi, R., Das, B., Paul, A., Tripathi, O.P. and Mishra, B.P. 2021. Biomass, carbon stock and soil physicochemical properties in plantation of East Siang district, Arunachal Pradesh, India. *Environ. Challenges* 4: 00191.

Das, D.K., Chaturvedi, O.P., Mandal, M.P., and Kumar, R. 2007. Reclamation of degraded soil through tree plantation-litter and fertility changes. *Indian For.* 133(5): 647.

Deb, S., Arunachalam, A. and Arunachalam, K. 2005. Cell-wall degradation and nutrient release pattern in decomposing leaf litter of *Bambusa tulda* Roxb. and *Dendrocalamus hamiltonii* Nees. in a bamboo-based agroforestry system in north-east India. *J. of Bamboo and Rattan* 4(3): 257-277.

Debnath. N., Nath, A.J., Reang,d., and Das, A.K. 2020. Gregarious flowering in Dendrocalamus longispathus (Kurz) Kurz in North East India. *Indian For*. 146(4): 359-360.

Dent, D.H., Bagchi, R., Robinson, D., Majalap-Lee, N., and Burslem, D.F. 2006. Nutrient fluxes via litterfall and leaf litter decomposition vary across a gradient of soil nutrient supply in a lowland tropical rain forest. *Plant and Soil* 288: 197-215.

Descheemaeker, K., Muys, B., Nyssen, J., Poesen, J., Raes, D., Haile, M., and Deckers, J. 2006. Litter production and organic matter accumulation in exclosures of the Tigray highlands, Ethiopia. *For. Ecol. and Manag.*233(1): 21–35.

Devi, A.S. and Singh, K.S. 2021. Carbon storage and sequestration potential in aboveground biomass of bamboos in Northeast India. *Sci. Rep*. 11(1): 837.

Devi, A.S. and Yadav, P.S. 2007. Wood and leaf litter decomposition of Dipterocarpus tuberculatus Roxb. In a tropical deciduous forest of Manipur. North East India. *Curr. Sci.* 93: 243–246.

Devi, M., Darlong, L., and Bhattacharyya, D. 2014. Dendrocalamus longispathus (Poaceae: Bambusoidae) in sporadic bloom in Tripura, India. *NeBIO* 5(1): 88-89.

Dey, T., Singh, M., Tamang, M., N, S.N., Nath, A.J., Shukla, G. and Chakravarty, S. 2023. Prioritizing Tree-Based Systems for Optimizing Carbon Sink in the Indian Sub-Himalayan Region. *Land* 12(6): 1155.

Dick, W. A. and Tabatabai, M. A. 1993. Significance and potential uses of soil enzymes, In: Metting, F.B. (ed.), *Soil Microbial Ecology*. Marcel Dekker, New York, pp. 95-127.

Dilly, O., Bloem, J., Vos. A., and Munch, J.C. 2004. Bacterial diversity in agricultural soils during litter decomposition. *Appl. Environ. Microbiol*. 70: 468–474.

Dinesh, K. 2015. Assessment of Soil Quality Parameters Under Different Land Uses in Barog-Dhillon Watershed in Solan District Of Himachal Pradesh. M.Sc.(For) thesis, Dr. YS Parmar University of Horticulture and Forestry, Nauni, Solan, 31p.

Doerr, S.H., Shakesby, R.A. and Walsh, R. 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth-Sci. Rev.* 51(1-4): 33-65.

Edmonds, R.L. 1984. Long term decomposition and nutrient dynamics in pacific silver fir needles in western Washington. *Can. J. For.Res*. 14: 395–500.

Edwards, C.A. and Heath, G.W. 1963. The role of soil animals in breakdown of leaf material. In: Doeksen, J. and Van der Drift, J. (eds), *Soil organisms*. North Holland Publishing Company, Amsterdam, pp 76–84.

Erdem, R. 2022. Change of Calcium Concentrations in Forest Soils by Plant Species and Soil Depth. Kastamonu University. *J. of Eng. and Sci.* 8(2): 122-127.

FSI [Forest survey of India].2021. India state of forest report. Bamboo resources of the country, pp. 175-183.

Fuke, P., Kumar, M., Sawarkar, A.D., Pandey, A. and Singh, L. 2021. Role of microbial diversity to influence the growth and environmental remediation capacity of bamboo: a review. *Ind.Crops and Products* 167: 113567.

Gaikwad, A.S., Ingle, S., Thite, M. and Rananavare, A. 2022b. Nutrient accumulation and distribution in different bamboo species under semi-arid climatic condition of Entisol. *The Pharma Innovation J.* 11(1): 156-161.

Gaikwad, A.S., Kale, S.D. and Ghadge, S.T. 2022a. Effect of different bamboo species on soil properties grown on Entisol of semi-arid climate. *The Pharma Innovation J.* 11(1): 829-835.

Gaikwad, A.S., Thite, M., and Rananavare, S.I.A. 2021. Effect of different bamboo species on growth attributing characters grown on Entisol of semi-arid climate. *The Pharma Innovation* 10(12): 1980-1985.

García-Palacios, P., Maestre, F.T., Kattge, J., and Wall, D.H. 2013. Climate and litter quality differently modulate the effects of soil fauna on litter decomposition across biomes. *Ecol. Lett.* 16(8): 1045-1053.

Garg, A., Das, S., Singh, Y.P. and Sharma, P. 2013. Exploring the Microbial Activities in the Rhizospheres of Exotic Bamboos. *Octa J. of Environ. Res.* 1(1): 30-38.

Garima.2013. Effect of bamboo species and integrated nutrient management on productivity of ginger crop. M.Sc. (For.) thesis, Dr. YS Parmar University of Horticulture and Forestry, Nauni, Solan, 47p.

Gartner, T.B. and Cardon, Z.G. 2004. Decomposition dynamics in mixed-species leaf litter. *Oikos* 104: 230–246.

Ge, X., Zeng, L., Xiao, W., Huang, Z., Geng, X., and Tan, B. 2013. Effect of litter substrate quality and soil nutrients on forest litter decomposition: A review. *Acta Ecol. Sinica* 33(2): 102–108.

Geisseler, D., Horwath, W.R. and Scow, K.M. 2011. Soil moisture and plant residue addition interact in their effect on extracellular enzyme activity. *Pedobiologia* 54(2): 71-78.

George, S.J. and Kumar, B.M. 1998. Litter dynamics and cumulative soil fertility changes in silvopastoral systems of a humid tropical region in central Kerala. India. *Int. Tree Crops J.* 9(4): 267-282.

Getahun, A., Kebede, Y., Tadese, Z., Mulatu, Y., and Adamu, F. 2023. Growth and biomass production of five exotic bamboo species in North-western Ethiopia. *Adv. in Bamboo Sci*. 4: 100030.

Giweta, M. 2020. Role of litter production and its decomposition, and factors affecting the processes in a tropical forest ecosystem: A review. *J. Ecol. and Environ.* 44(1): 1–9.

Gogoi, B. and Bhuyan, T.C. 2016. Physico-chemical properties and microbial biomass carbon of bamboo growing soils: a comparative study. *Indian For.* 142(8): 739-744.

Gosz, J.R., Likens, G.E., and Bormann, F.H. 1973. Nutrient release from decomposing leaf and branch litter in the Hubbard Brook Forest, New Hampshire. *Ecol. Monogr.* 43:173–191.

Gu, Y., Wang, P. and Kong, C.H. 2009. Urease, invertase, dehydrogenase and polyphenoloxidase activities in paddy soil influenced by allelopathic rice variety. *Eur. J. of Soil Biol.* 45(5-6): 436-441.

Guo, J.P., Ding, Y.X. and Zhang, Y.X. 2009. Decomposition process and nutrient dynamic of litterfall in a Larix rupprechtii stand in Guandishan Mountains. *Acta Ecol. Sinica,* 29: 5684-5695.

Gupta, R.P. and Dakshinamoorthy, C. 1980. Procedures for physical analysis of soil and collection of agrometeorological data. Indian Agricultural Research Institute, New Delhi, 293p.

Hättenschwiler, S., Tiunov, A.V., and Scheu, S. 2005. Biodiversity and litter decomposition in terrestrial ecosystems. *Annu. Rev. Ecol. Evol. Syst*.36: 191-218.

Heath, Dickinson, C.H., and Pugh, G.J.F. 1966. *Biology of Plant Litter Decomposition: 2 Vol.* Academic Press, London, pp. 132-140.

Hobbie, S.E. 1992. Effects of plant species on nutrient cycling. *Trends in Ecol. & Evol*. 7(10): 336-339.

Hossain, M.A., Kumar, S.M., Seca, G., Maheran, A.A., and Aini, A.S.N. 2018. Mass Propagation of *Dendrocalamus asper* By Branch Cutting. *J. Trop. For. Sci*.30:82–88.

Hua, T.U., Hong-Ling, H.U., Ting-Xing, H.U., Zhang, J., Xian-Wei, L.I., Li, L.I.U., Yin-Long, X.I.A.O., Gang, C.H.E.N. and Ren-Hong, L.I. 2014. Litterfall, litter decomposition, and nutrient dynamics in two subtropical bamboo plantations of China. *Pedosphere* 24(1): 84-97.

Hughes, J.W., Fahey, T.J., and Browne, B. 1987. A better seed and litter trap. *Can. J. of For. Res.* 17(12): 1623-1624.

INBAR [International Bamboo and Rattan Organization]. 2023. Why bamboo and rattan[online]. Available: https://www.inbar.int/why-bamboo-and-rattan[26 august 2023].

INBAR [International Bamboo and Rattan Organization].2018. INBAR news [online]. Available: http://terrafrica.org/wpcontent/uploads/2018/10/Bamboo-for-Land-Restoration.pdf

Irmler, U. 1982. Litter fall and nitrogen turnover in an Amazonian black water inundation forest. *Plant Soil* 67:355–358

Isaac, S. R., and Nair, M. A. 2005. Biodegradation of leaf litter in the warm humid tropics of Kerala, India. *Soil Biol. and Biochem*. 37(9): 1656–1664.

Isaac, S.R. and Nair, M.A. 2006. Litter dynamics in six multipurpose trees in a homegarden in Southern Kerala, India. *Agroforest. Syst.* 67: 203-213.

Jackson, M.L. 1958. *Soil chemical analysis*. Prentice Hall. Inc., Englewood Cliffs, NJ, 498p.

Jackson, M.L., 1973. *Soil chemical analysis*. Pentice hall of India Pvt. Ltd., New Delhi, India, pp.151-154.

Jamaludheen, V. and Kumar, B.M. 1999. Litter of multipurpose trees in Kerala, India: variations in the amount, quality, decay rates and release of nutrients. *For. Ecol. and Manag.* 115(1): 1-11.

Jamaludheen, V.1994. Biomass production and root distribution pattern of selected fast growing multi-purpose tree species. M.Sc. (For.) thesis, Kerala Agricultural University, Thrissur, 66p.

Jha, D.K., Sharma, G.D. and Mishra, R.R. 1992. Soil microbial population numbers and enzyme activities in relation to altitude and forest degradation. *Soil Biol. and Biochem*. 24(8): 761-767.

Jijeesh, C.M. and Seethalakshmi, K.K. 2015. Litter production and decomposition dynamics of *Bambusa balcooa* Roxb., a bamboo species introduced to Kerala state of India. Mohanan *et al.*(eds), *Prospects in Forestry and Agriculture*. KFRI, Peechi, pp. 101-104.

Jijeesh, C.M. and Seethalakshmi, K.K. 2016a. Litterfall and decomposition dynamics of six year old *Bambusa balcooa* Roxb. homestead block plantation in Palakkad, central Kerala. *Range Manag. and Agrofor*. 37(2): 155-161.

Jijeesh, C.M. and Seethalakshmi, K.K. 2016b. Litter deposition, decomposition and nutrient release dynamics of six year old *Ochlandra travancorica* gamble: an endemic reed bamboo of western ghats. *Plant Arch.* 16(1): 31-36.

Jijeesh, C.M., Kuruvilla, T., and Seethalakshmi, K.K., 2021. Nutrient locking in Biomass and Soil of *Munrochloa ritchiei* and *Ochlandra setigera*, two endemic bamboo species of Western Ghats. *Int. J. of Adv. Biol. Res.* 11(1): 18-23.

Johnson, L.F. and Curl, E.A. 1971. *Methods for research on the ecology of soil-borne plant pathogens*. Burgess Publishing Company, Minneapolis, 247p.

Joshi, A.P., Sundriyal, R.C., and Baluni, D.C. 1991. Nutrient dynamics of a lower Siwalik bamboo forest in the Garhwal Himalaya, India. *J. Trop. For. Sci.* 3(3): 238-250.

Judziewicz, E.J., Clark, L.G., Londono, X., and Stern, M.J. 1999. *American bamboos*. Smithsonian Institution Press, Washington, DC, 392p.

Kallenbach, C.M., Frey, S.D. and Grandy, A.S. 2016. Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls. *Nat. Commun.* 7(1): 13630.

Kaushal, R., Kumar, A., Alam, N.M., Singh, I., Mandal, D., Tomar, J.M.S., Mehta, H., Lepcha, S.T.S., Long, T.T., and Durai, J. 2021b. Assessment of eco-hydrological parameters for important sympodial bamboo species in Himalayan foothills. *Environ. Monitoring and Assess.* 193: 1-13.

Kaushal, R., Kumar, T., Singh, A., Tomar, J.M.S., Mehta, H., Chandran, M., Lepcha, S.T.S., and Durai, J. 2021c. Introduction of *Dendrocalamus stocksii* (Munro.) in the Northwestern Himalayan foothills for sustainable production and resource conservation. *Curr. Sci.* 121(9): 00113891.

Kaushal, R., Singh, I., Thapliyal, S.D., Gupta, A.K., Mandal, D., Tomar, J.M.S., Kumar, A., Alam, N.M., Kadam, D., Singh, D.V., and Mehta, H. 2020. Rooting behaviour and soil properties in different bamboo species of Western Himalayan Foothills, *India. Sci. Rep*. 10(1): 4966.

Kaushal, R., Tewari, S., Banik, R.L., Thapliyal, S.D., Singh, I., Reza, S., and Durai, J. 2019. Root distribution and soil properties under 12-year-old sympodial bamboo plantation in Central Himalayan Terai Region, India. *Agrofor. Syst.* 94: 917–932.

Kaushal, R., Tewari, S., Thapliyal, S.D., Kumar, A., Roy, T., Islam, S., Lepcha, S.T.S. and Durai, J. 2021a. Build-up of labile, non-labile carbon fractions under fourteen-year-old bamboo plantations in the Himalayan foothills. *Heliyon,* 7(8): 07850.

Kaushal, R., Verma, K.S., Chaturvedi, O.P. and Alam, N.M. 2012. Leaf litter decomposition and nutrient dynamics in four multipurpose tree species. *Range Manag. and Agrofore*. 33(1): 20-27.

KFRI [Kerala Forest Research Institute] 2009. Status Of Bamboo Sector in Kerala[online]. Available: https://forest.kerala.gov.in/images/gwarm/21stusbmbo.pdf [20 Aug. 2023].

Kittur, B.H., Sudhakara, K., Kumar, B.M., Kunhamu, T.K., and Sureshkumar, P. 2017. Effects of clump spacing on nutrient distribution and root activity of *Dendrocalamus strictus* in the humid region of Kerala, peninsular India. *J. For. Res.* 28: 1135-1146.

Kozlowski, T. T. 1973. Extent and Significance of Shedding of Plant Parts. In: Kozlowski, T. T. (ed.), *Shedding of Plants Parts*. Academic Press, London, pp. 1-44.

Krishna, M. P. and Mohan, M. 2017. Litter decomposition in forest ecosystems: a review. *Energy, Ecol. and Environ*. 2(4): 236–249.

KSBM [Kerala state bamboo mission].2022. KSBM bamboo in Kerala [online]. Available: http://keralabamboomission.org/index.php/about-us/bamboo-in-Kerala. [26 Jul. 2022].

Kucera, C.L. 1959. Weathering characteristics of deciduous leaf litter. *Ecology* 40(3): 485-487.

Kumar, B.M. 1997. Bamboos in the homegardens of Kerala: A shrinking resource base. *J. Non-timber For. Products* 4(3/4): 156-159.

Kumar, B.M. 2008. Litter dynamics in plantation and agroforestry systems of the tropics-a review of observations and methods. In: Batish, D.R., Kohli, R.K., Jose, S., and Singh, H.P. (eds), *Ecological basis of agroforestry*. CRC press, pp.181-216.

Kumar, B.M. and Deepu, J.K. 1992. Litter production and decomposition dynamics in moist deciduous forests of the Western Ghats in Peninsular India. *For. Ecol. and Manag*. 50(3-4): 181-201.

Kumar, M. and Ramesh, M. 2000. Diversity of bamboos in Kerala and their conservation. In *Proceedings of the Twelfth Kerala Science Congress*, Kumily, STEC, Trivandrum, pp. 209-212.

Kumar, M., Joshi, M. and Todaria, N.P. 2010. Regeneration status of a sub-tropical *Anogeissus latifolia* forest in Garhwal Himalaya, India. *J. of For. Res*. 21: 439-444.

Kumar, P.S., Shukla, G., Nath, A.J., and Chakravarty, S. 2022. Soil properties, litter dynamics and biomass carbon storage in three-Bamboo species of sub-himalayan region of Eastern India. *Water, Air, & Soil Pollut.* 233(1): 12.

Kumari, Y. and Bhardwaj, D.R., 2017. Effect of various bamboo species on soil nutrients and growth parameters in Mid hills of HP, India. *Int. J. of Chem. Stud*. 5(4): 19-24.

Kumari, Y. and Bhardwaj, D.R., 2019. Bioproduction and nutrient cycling in seven bamboo species in subtropical Indian Himalayas. *J. of Tree Sci.* 38(2): 1-12.

Kunhamu, T.K., Kumar, B.M. and Viswanath, S. 2009. Does thinning affect litterfall, litter decomposition, and associated nutrient release in Acacia mangium stands of Kerala in peninsular India?. *Can. J. of For. Res*. 39(4): 792-801.

Kunhamu, T.K., Kumar, B.M., Assif, P.K. and Jayadevan, C.N. 1994. Litter yield and decomposition under Acacia auriculiformis. *Nitr. Fixing Tree Res. Rep*. 12: 29-32.

Kuruvilla, T., Jijeesh, C.M. and Seethalakshmi, K.K. 2016. Litter production and decomposition dynamics of a rare and endemic bamboo species *Munrochloa ritcheyi* of Western Ghats, India. *Trop. Ecol*. 57(3): 601-606.

Lakshmy, A. 2014. Soil productivity changes under selected indigenous forest tree species with special reference to beneficial microflora. M.Sc. (For.) thesis, Kerala Agricultural University, Thrissur, 61p.

Lal, J., Naugraiya, M.N., Anchal, N.K., Tirkey, J., and Patel, D.K. 2022. Growth performance, biomass, carbon storage and carbon dioxide release abatement of bamboo plantation in Chhattisgarh plains of India. *Curr. Sci.* 123(4): 00113891.

Laskowski, R. and Berg, B. 2006. *Litter decomposition: guide to carbon and nutrient turnover* (38). Elsevier Academic Press, Amsterdam, 24p.

Li, L., Xia, T. and Yang, H. 2022. Seasonal patterns of rhizosphere microorganisms suggest carbohydrate-degrading and nitrogen-fixing microbes contribute to the attribute of full-year shooting in woody bamboo *Cephalostachyum pingbianense*. *Front. Microbiol.* 13: 1033293.

Liese, W. and Köhl, M. 2015. *Bamboo The plant and its uses*. Springer International Publishing, Switzerland, 252p.

Li-Hua, T.U., Hong-Ling, H.U., Ting-Xing, H.U., Zhang, J., Xian-Wei, L.I., Li, L.I.U., Yin-Long, X.I.A.O., Gang, C.H.E.N., and Ren-Hong, L.I. 2014. Litterfall, litter decomposition, and nutrient dynamics in two subtropical bamboo plantations of China. *Pedosphere*, 24(1): 84-97.

Lobovikov, M., Ball, L., Guardia, M., and Russo, L. 2007. World bamboo resources: a thematic study prepared in the framework of the global forest resources assessment 2005(No. 18). Food and Agriculture Organization of the United Nations, 63p.

Lousier, J.D. and Parkinson, D. 1978. Chemical element dynamics in decomposing leaf litter. *Can. J. Bot.* 54: 2795-2812

Madathil, J.C. and Kodikunnath, S.K. 2018. Litter fall, decomposition and nutrient release dynamics of *Thyrsostachys oliveri* gamble in humid tropics of Kerala, Southern India. *Soil & Environ.* 37(2): 152-159.

Mahesh, K.S.1997. Studies on Microbial Diversity and their Activity in Soil Under Bamboo Plantation. M.Sc.(Ag) thesis, University Of Agricultural Sciences GKVK ,Bangalore, 72p.

Maini, A., Sharma, V. and Sharma, S. 2020. Assessment of soil carbon and biochemical indicators of soil quality under rainfed land use systems in Northeastern region of Punjab, India. *Carbon Manag*. 11(2): 169-182.

Martin, J.P. 1950. Use of acid, rose bengal, and streptomycin in the plate method for estimating soil fungi. *Soil Sci*. 69(3): 215-232.

Maviton, M.E. and Sankar, V.R. 2023. *Global Priority Species of Economically Important Bamboo.* INBAR, Series No. 44, China, pp. 44p.

McClure, F. A. 1966. *The Bamboos*. Harvard University Press, Cambridge, Massachusetts, 210p.

Meentemeyer, V. 1978. Macroclimate and lignin control of litter decomposition rates. *Ecology* 59(3): 465-472.

Mohd-Aizat, A., Mohamad-Roslan, M.K., Sulaiman, W.N.A. and Karam, D.S. 2014. The relationship between soil pH and selected soil properties in 48 years logged-over forest. *Int. J. of Environ. Sci.* 4(6): 1129.

Mukshi, M. 2013. Depth wise distribution of nutrient elements in high density apple orchards and their relationship with fruit yield and quality. PhD (Ag) thesis, SKUAST, Kashmir,74p.

Muraleedharan, P. K., Anitha, V., Krishnankutty, C. N., Gnanaharan, R., Vijayakumaran, P., Sankar, N. S., and Seethalakshmi, K. K. 2007. Bamboo sector in Kerala: Base line data generation for developing an action plan. Research Report (No. 291), 105p.

Myers, R. J. K., Palm, C. A., Cuevas, E., Gunatilleke, I. U. N., Brossard, M. 1994. The synchronisation of nutrient mineralization and plant nutrient demand. In: Woomer, PL.and Swift, M. J.(eds), The biological management of tropical soil fertility. New York (NY): TSBF-John Wiley and Sons,pp. 81–116.

Naithani, H.B., 2015. Gregarious flowering of Dendrocalamus longispathus in Mizoram, India. *Indian For.* 141(8): 893-895.

Nanganoa, L.T., Okolle, J.N., Missi, V., Tueche, J.R., Levai, L.D. and Njukeng, J.N. 2019. Impact of different land-use systems on soil physicochemical properties and macrofauna abundance in the humid tropics of Cameroon. *Appl. and Environ. Soil Sci*. 2019:9.

Narasinmhamurty, C.M., Nadanwar, A., and Pandey, C.N. 2013. A study on physico-mechanical properties of Thyrsostachy ssiamensis (Kurz) Gamble and Dendrocalmus membranaceus (Munro) in Tumkur district, Karnataka, India. *Int. J. Curr. Microbiol. and Appl. Sci.* 2(2): 62-66.

Narendra, S. 2017. Studies on growth behaviour and soil characteristics under different bamboo species in mollisols of Uttarakhand. M.Sc. (For) thesis, G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand 58p.

Nath, A.J. and Das, A.K. 2011. Decomposition dynamics of three priority bamboo species of homegardens in Barak Valley, Northeast India. *Trop. Ecol*. 52(3): 325-330.

Nath, A.J., Lal, R. and Das, A.K. 2015. Ethnopedology and soil properties in bamboo (Bambusa sp.) based agroforestry system in Northeast India. *Catena* 135: 92-99.

Naugraiya M.N. 2015. Role of *Dendrocalamus strictus* in locking of carbon and NPK nutrients under plantation forestry. National Workshop on carbon sequestration in forest and non-forest ecosystem. Jhansi. February 16-17,2015, pp. 42-50.

NBM [National Bamboo Mission].2019. Operational guidelines of National Bamboo Mission [online]. Available: https://nbm.nic.in/. [26 Aug. 2023].

Neal, J.L., Larson, R.I. and Atkinson, T.G. 1973. Changes in rhizosphere populations of selected physiological groups of bacteria related to substitution of specific pairs of chromosomes in spring wheat. *Plant and Soil* 39: 209-212.

Negi, H., Tewari, S., Dubey, A., Kaushal, R., and Bhatt, P. 2022. Status of biodiversity in bamboos of India. *Int. J. of Innovative Hortic*. 11(2): 288-296.

Noman, M., David, A.A., Thomas, T., Swaroop, N. and Hasan, A. 2021. Assessment of Physico-chemical Properties of Soil in Dadrol Block, Shahjahanpur District, Uttar Pradesh, India. *Int. J. Curr. Microbiol. Appl. Sci.* 10(07): 30-42.

O'Connell, A. M. and Sankaran, K. V. 1997. Organic matter accretion, decomposition and mineralisation. In: Nambiar, E. K. S. and Brown, A. G.(eds), *Management of Soil, Nutrients and Water in Tropical Plantation Forests.* Australian Centre for International Agricultural Research (ACIAR), Canberra, pp. 443–480.

O'connor, P.J., Covich, A.P., Scatena, F.N., and Loope, L.L. 2000. Non-indigenous bamboo along headwater streams of the Luquillo Mountains, Puerto Rico: leaf fall, aquatic leaf decay and patterns of invasion. *J. of Trop. Ecol.* 16(4): 499-516.

Olson, J.S. 1963. Energy storage and the balance of producers and decomposers in ecological systems. *Ecology* 44(2): 322-331.

Pandey, A.K. and Ojha, V. 2013. Standardization of harvesting age of bamboo shoots with respect to nutritional and anti-nutritional components. *J.of For. Res*. 24: 83-90.

Pandey, R., Paul, V., Das, M., Meena, M. and Meena, R.C. 2017. Plant growth analysis. Manual of ICAR Sponsored Training Programme on "Physiological Techniques to Analyze the Impact of Climate Change on Crop Plants, pp.103-107.

Panhwar, Q.A., Naher, U.A., Shamshuddin, J., Othman, R. and Ismail, M.R. 2016. Applying limestone or basalt in combination with bio-fertilizer to sustain rice production on an acid sulfate soil in Malaysia. *Sustainability* 8(7): 700.

Pant, S.C. and Tiwari, S.C. 1992. Litter fall and litter decomposition in a montane oak forest of Garhwal Himalaya. *Trop. Ecol*. 33(1): 103-109.

Paustian, K., Collins, H.P. and Paul, E.A. 1997. Management controls on soil carbon. In: Paul, E.A., Paustian, K., Elliott, E.A. and Cole, C.V. (eds.), *Soil Organic Matter in Temperate Agroecosystems: Long-term Experiments in North America*, CRC Press, Boca Raton, 1549p.

Pereira F. A., Giongo, V., Simoes, W.L. and Lal, R. 2016. Nutrients dynamics in soil solution at the outset of no-till implementation with the use of plant cocktails in Brazilian semi-arid. *Afr. J. of Agric. Res*. 11(4): 234-246.

Perez-Harguindeguy, N., Diaz, S., Cornelissen, J.H.C., Venramini,F., Cabido, M., and Castellanos, A. 2000. Chemistry and toughness predict leaf litter decomposition rates over a wide spectrum of functional types and taxa in central Argentina. *Plant Soil* 218: 21–30.

Prasath, C.N.H., Sudarshan, A., and Goroji, P.T. 2014. Quantification of litter fall and assessment of nutrient composition in bamboo (*Bambusa vulgaris* var. Vulgaris) plantation. *Int. J. of For. and Crop Improv*. 5(2): 54-60.

Prescott, C.E. 2005. Do rates of litter decomposition tell us anything we really need to know? *For. Ecol. and Manag*. 220(1-3): 66-74.

R. J. K. Myers, C. A. Palm, E. Cuevas, I. U. K. Gunatilleke and M. Brossard. 1994.The synchronization of nutrients mineralization and plant demand. In: Woomer P. L. and Swifted M. J.(eds), *The Biological Management of Tropical Soil Fertility*. Wiley Sayee, New York, pp. 81–116.

Rakesh, A.P., Kumari, V., Shekhar, D. and Prasad, R.P. 2020. Soil Sulphur status and response of crops to Sulphur application in Indian soils: A review. *J. of Pharmacognosy and Phytochemistry* 9(3): 1406-1410.

Rao, A.N., Ramanatha Rao, V. and Williams, J.T., 1998. *Priority species of bamboo and rattan.* IPGRI-APO, Serdang, Malaysia,95 p.

Rawat, N., Nautiyal, B. P., and Nautiyal, M. C. 2010. Annual nutrients budget for the grazed and ungrazed sites of an alpine expanse in North-West Himalaya, India. *The Environ*. 30: 54–66.

Rutigliano, F.A., Alfani, A., Bellini, L. and De Santo, A.V. 1998. Nutrient dynamics in decaying leaves of Fagus sylvatica L. and needles of Abies alba Mill. *Biol. Fert.of Soils* 27(2): 119-126.

Sailo, L., Lalnunmawia, F., Upadhyaya, K., Kumar, K.S. and Tripathi, S.K. 2020. Floral morphology and impact of flowering of Dendrocalamus longispathus Kurz on soil physicochemical properties in natural forests of Mizoram, Northeast, India. *Environ. and Ecol.* 38(3): 534-543.

Samritika, T. 2013. Belowground architecture and carbon stocks of silver oak (Grevillea robusta A. Cunn.) trees. M.Sc. (For.) thesis, Kerala Agricultural University, Thrissur, 150p.

Sankaran, K.V. 1993. Decomposition of leaf litter of albizia (*Paraserianthes falcataria*), eucalypt (*Eucalyptus tereticornis*) and teak (*Tectona grandis*) in Kerala, India. *For. Ecol. and Manag.* 56(1-4): 225-242.

Scarascia, M.G., De Angelis, P., Sabatti, M., Calfapietra, C., Ceulemans, R., Peressotti, A. and Miglietta, F. 2000. A FACE experiment on short rotation, intensive poplar plantation: objective and experimental set up of POPFACE. In: Sutton, M.S., Moreno, J.M., and van der Putten, W.H.I. (eds.), *Terrestrial Ecosystem Research in Europe: Successes, Challenges and Policy*. Office of Official Publication of the European Communities, Luxembourg, pp. 139–140

Schaefer, M. and Schauermann, J. 1990. The soil fauna of beech forests: Comparison between a mull and a modern soil. *Pedobiologia* 34(5):299–314.

Seeber, J., Scheu, S., and Meyer, E. 2006. Effects of macro-decomposers on litter decomposition and soil properties in alpine pastureland: a mesocosm experiment. *Appl. Soil Ecol.* 34(2-3): 168-175.

Seethalakshmi K.K. and Kumar M.M.S. 1998. Bamboos of India; A compendium. Bamboo information centre, Kerala Forest Research Institute, Peechi and International Network for Bamboos and Rattan, Beijing, 43p.

Seethalakshmi, K.K., Jijeesh, C.M. and Balagopalan, M. 2009. Bamboo plantations: an approach to Carbon sequestration. In: Manoharan, T.M., Sinha, V.K., Singh, L and Khanduri, S.K. (eds), *Proceedings of National Workshop on Global Warming and its Implications for Kerala,* 19-21 January 2019, Peechi. Kerala Forest Research Institute, pp. 151-161.

Selassie, Y.G. and Ayanna, G. 2013. Effects of different land use systems on selected physico-chemical properties of soils in Northwestern Ethiopia. *J. of Agric.Sci.* 5(4): 112.

Semwal, R.L., Maikhuri, R.K., Rao, K.S., Sen, K.K., and Saxena, K.G. 2003. Leaf litter decomposition and nutrient release patterns of six multipurpose tree species of central Himalaya, India. *Biomass and Bioenerg*. 24(1): 3-11.

Seneviratne, G. 2000. Litter quality and nitrogen release in tropical agriculture: a synthesis. *Biol. Fertil. Soils* 31(1):60–64.

Shanij, K., Suresh, S., Jilesh, V. and Nayar, T.S. 2023. Leaf litter production and decomposition in a Riverine Mangrove Forest in India. *Wetlands Ecol. and Manag.* 54: 1-19.

Shankar, T. 2022. Growth and productivity as function of site quality and age in teak plantations of Nilambur, Kerala. M.Sc.. (For.) thesis, Kerala Agricultural University, Thrissur, 99p.

Shanmughavel, P., Peddappaiah, R.S. and Muthukumar, T. 2000. Litter production and nutrient return in Bambusa bambos plantation. *J. of Sustain. For*. 11(3):71-82.

Sharma, M.L. and Nirmala, C. 2015. Bamboo Diversity of India: An update. In: Nirmala, C.(ed.), *10th World Bamboo Congress proceedings*, 17-22 September 2015, Damyang. Korea, 13p.

Shiau, Y.J., Wang, H.C., Chen, T.H., Jien, S.H., Tian, G. and Chiu, C.Y. 2017. Improvement in the biochemical and chemical properties of badland soils by thorny bamboo. *Sci. Rep.* 7(1): 40561.

Shilpkar, P., Shah, M.C., Modi, K.R. and Patel, S.M. 2010. Seasonal changes in microbial community structure and nutrients content in rhizospheric soil of Aegle marmelos tree. *An. of For. Res.* 53(2): 135-140.

Singh A K, Singh A K and Singh A. K. 2019. Study of available potassium by different extracting reagents and fertility status of soils of Bairia subdivision of Ballia, U.P. *Asian J. of Sci. and Technol.* 9(04): 9584-9586.

Singh, A.N. and Singh, J.S. 1999. Biomass, net primary production and impact of bamboo plantation on soil redevelopment in a dry tropical region. *For. Ecol. and Manag*. 119(1-3): 195-207.

Singh, I.S., Awasthi, O.P., Singh, R.S., More, T.A. and Meena, S.R. 2012. Changes in soil properties under tree species. *Indian J. of Agric. Sci*. 82(2): 146.

Singh, K.A. 2002. Boon of bamboo resources in Northeast India. In: Singh K.A. (ed.), *Resource management perspective of Arunachal agriculture*. ICAR Research Complex for NEH Region. A.P. Centre, Basar. Arunachal Pradesh. India, pp.69-112.

Singh, K.A. and Kochhar, S.K. 2005. Effect of clump density/spacing on the productivity and nutrient uptake in Bambusa pallida and the changes in soil properties. *J. Bamboo Rattan* 4(4): 323-334.

Singh, K.P., Devi, S.P., Devi, K.K., Ningombam, D.S., and Athokpam, P. 2010. Bambusa tulda Roxb. in Manipur State, India: exploring the local values and commercial implications. *Not. Sci. Biol*. 2(2): 35-40.

Singh, K.P., Singh, P.K. and Tripathi, S.K. 1999. Litterfall, litter decomposition and nutrient release patterns in four native tree species raised on coal mine spoil at Singrauli, India. *Biol. and Fertil. of Soils* 29: 371-378.

Smith, W.H. 1969. Release of organic materials from the roots of tree seedlings. *For. Sci*. 15(2): 138-143.

Solomon, T., Moon, H., Abebe, S., Minale, A.S., and Teketay, D. 2020. Promoting bamboo-based agroforestry for enhancing ecosystem services from degraded lands. In: Dagar, J.C., Gupta, S.R., and Teketay, D.(eds), *Agroforestry for Degraded Landscapes: Recent Advances and Emerging Challenges,* Springer publisher, pp. 423-444.

Sowmya, C., Jagadish, M.R. and Syam, V. 2015. Cultivation prospects of Dendrocalamus asper backer for edible shoots in semiarid and humid tropics of peninsular India. *Int. J. Plant Anim. Environ. Sci.* (5): 95–101.

Sreekala, M.V. 1997. Organic Recycling Through Cocoa Litter. MSc (Ag) thesis, Kerala Agricultural University, Thrissur, 92p.

Stapleton, C. 1997. The morphology of woody bamboos. In: Champman, G.P. (ed.), *The Bamboo*. Linnean Society Symposium Series, Academic Press Limited, pp. 251-268.

Stinner, B.R., Crossley Jr, D.A., Odum, E.P., and Todd, R.L. 1984. Nutrient budgets and internal cycling of N, P, K, Ca, and Mg in conventional tillage, no-tillage, and old-field ecosystems on the Georgia piedmont. *Ecology* 65(2): 354-369.

Subbiah, B.V. and Asija, G.L. 1956. A rapid procedure for the estimation of available nitrogen in soils. *Curr. Sci.* 25(8): 259-260.

Subhani, A., Changyong, H., Zhengmiao, Y., Min, L. and El-Ghamry, A. 2001. Impact of soil environment and agronomic practices on microbial/dehydrogenase enzyme activity in soil. A review. *Pakist. J. of Biol. Sci*. 4(3): 333-338.

Sujatha, M.P. 1999. Characterisation of Soils Under Reed (Ochlandra Travancorica Benth.) In the Western Ghats. PhD (Ag) thesis, Kerala Agricultural University, Thrissur, 54p.

Sujatha, M.P., Jose, A.I. and Sankar, S. 2003. Leaf litter decomposition and nutrient release in reed bamboo (*Ochlandra travancorica*). *J. Bamboo and Rattan* 2:65-78.

Swift, M.J., Heal, O.W., Anderson, J.M. 1979. Decomposition in terrestrial ecosystems. In: Anderson, D.J., Greig, P., Pitelka, F.A. (eds), *Studies in ecology*. University of California Press, Berkeley, pp 167–219.

Tamang, M.; Chettri, R.; Vineeta; Shukla, G.; Bhat, J.A.; Kumar, A.; Kumar, M.; Suryawanshi, A.; Cabral-Pinto, M.; Chakravarty, S. 2021. Stand Structure, Biomass and Carbon Storage in *Gmelina arborea* Plantation at Agricultural Landscape in Foothills of Eastern Himalayas. *Land* 10: 387.

Tan, X., Kan, L., Su, Z., Liu, X. and Zhang, L. 2019. The composition and diversity of soil bacterial and fungal communities along an urban-to-rural gradient in South China. *Forests* 10(9): 797.

Tariyal, K., Upadhyay, A., Tewari, S. and Melkania, U. 2013. Plant and soil carbon stock and carbon sequestration potential in four major bamboo species of North India. *J. of Adv. Lab. Res. in Biol.* 4(3): 100-108.

Taylor, B.R., Parkinson, D. and Parsons, W.F. 1989b. Nitrogen and lignin content as predictors of litter decay rates: a microcosm test. *Ecology* 70(1): 97-104.

Taylor, B.R., Parsons, W.F.J. and Parkinson, D. 1989a. Decomposition of Populus tremuloides leaf litter accelerated by addition of Alnus crispa litter. *Can. J. For. Res*. 19: 647-679.

Tejkaran, P. 2014. Soil productivity changes under selected exotic forest tree species with special reference to beneficial microflora. M.Sc. (For) thesis, Kerala Agricultural University, Thrissur, 51p.

Tewari, S., Negi, H. and Kaushal, R. 2019. Status of Bamboo in India. *Int. J. of Econ. Plants* 6:30-39.

Thomas, K., Jijeesh, C.M., and Seethalakshmi, K.K. 2014. Litter production, decomposition, and nutrient mineralization dynamics of Ochlandra setigera: A rare bamboo species of Nilgiri Biosphere Reserve, India. *J. of For. Res.* 25: 579-584.

Tian, Q., Jiang, Y., Tang, Y., Wu, Y., Tang, Z. and Liu, F. 2021. Soil pH and organic carbon properties drive soil bacterial communities in surface and deep layers along an elevational gradient. *Front. Microbiol.*12: 646124.

Tiwari, S.C., Tiwari, B.K. and Mishra, R.R. 1987. The influence of moisture regimes on the population and activity of soil microorganisms. *Plant and Soil* 101: 133-136.

Torreta, N.K. and Takeda, H. 1999. Carbon and nitrogen dynamics of decomposing leaf litter in a tropical hill evergreen forest. *Eur. J. of Soil Biol*. 35(2): 57-63.

Tripathi, O.P., Pandey, H.N. and Tripathi, R.S. 2009. Litter production, decomposition and physico-chemical properties of soil in 3 developed agroforestry systems of Meghalaya, Northeast India. *Afr. J. of Plant Sci*. 3(8): 160-167.

Tripathi, S. K. and Singh, K. P. 1992. Abiotic and litter quality control during the decomposition of different plant parts in a dry tropical bamboo savanna in India. *Pedobiologia* 36: 241–256.

Tripathi, S.K. and Singh, K.P. 1995. Litter dynamics of recently harvested and mature bamboo savannas in a dry tropical region in India. *J. of Trop. Ecol*. 11(3): .403-417.

Tripathi, S.K., Sumida, A., Shibata, H., Ono, K., Uemura, S., Kodama, Y. and Hara, T., 2006. Leaf litterfall and decomposition of different above-and belowground parts of birch (Betula ermanii) trees and dwarf bamboo (Sasa kurilensis) shrubs in a young secondary forest in Northern Japan. *Biol. and Fertil. of Soils* 43: 237-246.

Tu, Z., Chen, L., Yu, X. and Zheng, Y. 2014. Rhizosphere soil enzymatic and microbial activities in bamboo forests in southeastern China. *Soil Sci. and plant Nutr*. 60(2): 134-144.

Tu, Z., Chen, L., Yu, X., and Zheng, Y., 2013. Effect of bamboo plantation on rhizosphere soil enzyme and microbial activities in coastal ecosystem. *Food. Agri. Env*. 2(3): 2333-2338.

Turner, J. and Lambert, M.J. 1988. Soil properties as affected by Pinus radiata plantations. *N. Z. J. of For. Sci.* 18(1): 77-91.

Ueda, K. 1960. Studies on the physiology of bamboo, with reference to practical application. *Biology* 30: 167.

Upadhyaya, K., Arunachalam, A. and Arunachalam, K. 2003. Microbial biomass and physico-chemical properties of soil under the canopy of *Bambusa balcooa* Roxb. and *Bambusa pallida* Munro. *Indian J. of Soil Conserv.* 31: 152-156.

Upadhyaya, K., Arunachalam, A., Arunachalam, K. and Das, A.K. 2008. Aboveground biomass and productivity appraisal of four important bamboo species growing along different altitudinal regimes in Arunachal Pradesh. *J. Bamboo Rattan* 7: 219-234.

Uthappa, A.R. 2021. Assessment of ecosystem services under different land use systems in semiarid conditions. PhD (For) thesis, University of Agricultural Sciences, Bangalore,81p.

Vanlalfakawma, D.C., Malsawmkima, B., and Tripathi, S.K. 2021. Gregarious flowering of a geriatric semelparous bamboo-Bambusa tulda Roxb. in Mizoram, India. *Curr. Sci*. 120(7): 1142-1143.

Veen, G.F., Sundqvist, M.A., and Wardle, D.A. 2015.Environmental factors and traits that drive plant litter decomposition do not determine home-field advantage effects. *Funct. Ecol*.29: 981–991.

Venkatesh, M.S., Bhatt, B.P., Kumar, K., Majumdar, B. and Singh, K. 2005. Soil properties influenced by some important edible bamboo species in the Northeastern Himalayan region. India. *J. of Bamboo and Rattan* 4(3): 221-230.

Viswanath, S., Sreekumar, V.B. and Sruthi, S. 2021. *Bambusa balcooa* roxb: a multi-utility bamboo for domestication. KSCSTE-Kerala Forest Research Institute, Peechi, Kerala, India, 43p.

Viswanath, S., Srivastava, C.K.A., Joshi,G., Chandramouli, S., and Joshi, S.C. 2013. *Dendrocalamus brandisii* (Munro) Kurz. *An ideal bamboo species for domestication in humid tropics,* IWST Technical Bulletin No. 12, Bangalore, pp. 1-20.

Vogt, K. A., Grier, C. C., and Vogt, D. J. 1986. Production, Turnover, and Nutrient Dynamics of Above- and Belowground Detritus of World Forests. *Adv. in Ecol. Res*. 15: 303–377.

Walkley, A. and Black, I.A. 1934. An examination of the digestion method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* 34: 29-38.

Wang, F.E., Chen, Y.X., Tian, G.M., Kumar, S., He, Y.F., Fu, Q.L., and Lin, Q. 2004. Microbial biomass carbon, nitrogen and phosphorus in the soil profiles of different vegetation covers established for soil rehabilitation in a red soil region of southeastern China. *Nutr. Cycling in Agroecosystems* 68(2): 181-189.

Waring, R.H. and Schlesinger, W.H. 1985. Forest ecosystems concepts and management In: *Decomposition and Forest Soil Development*, Academic Press, Inc. New York. pp. 181-210

Watanabe, F.S. and Olsen, S.R. 1965. Test of an ascorbic acid method for determining phosphorus in water and NaHCO3 extracts from soil. *Soil Sci. Soc. of Am. J.* 29(6): 677-678.

White, D. L., Haines, B. L., and Boring, L. R. 1988. Litter decomposition in southern Appalachian black locust and pine- hardwood stands: litter quality and nitrogen dynamics. *Can. J. of F. Res*. 18(1): 54–63.

Wibowo, H. and Kasno, A. 2021. Soil organic carbon and total nitrogen dynamics in paddy soils on the Java Island, Indonesia. In *IOP Conference Series: Earth and Environmental Science* 648 (1): 012192

Wieder, R. K., and Wright, S. J. 1995. Tropical Forest Litter Dynamics and Dry Season Irrigation on Barro Colorado Island, Panama. *Ecology* 76(6): 1971–1979.

Williams, C.H. and Steinbergs, A. 1959. Soil sulphur fractions as chemical indices of available sulphur in some Australian soils. *Aust. J. of Agric. Res*. 10(3): 340-352.

Wu, X., Wang, L., An, J., Wang, Y., Song, H., Wu, Y. and Liu, Q., 2022. Relationship between Soil Organic Carbon, Soil Nutrients, and Land Use in Linyi City (East China). *Sustainability* 14(20): 13585.

Xu, J., Liu, B., Qu, Z.L., Ma, Y. and Sun, H., 2020. Age and species of Eucalyptus plantations affect soil microbial biomass and enzymatic activities. *Microorganisms* 8(6): 811.

Yourmila, K. 2017. Biomass Production, Nutrient Cycling and Carbon Sequestration Potential Of Bamboo Plantations In Mid-Hills, Sub-Montane And Low Hills Of Himachal Pradesh. PhD (For) thesis, Dr. Y.S.P.U.H.F, Nauni, Solan ,85p.

Zhang, J., Lv, J., Li, Q., Ying, Y., Peng, C., and Song, X. 2017. Effects of nitrogen deposition and management practices on leaf litterfall and N and P return in a Moso bamboo forest. *Biogeochemistry* 134: 115-124.

Zhang, M.M., Fan, S.H., Guan, F.Y., Yan, X.R., and Yin, Z.X. 2020. Soil bacterial community structure of mixed bamboo and broad-leaved forest based on tree crown width ratio. *Sci. Rep.*10(1): 1-11.

Zheng, X., Lin, S., Fu, H., Wan, Y., and Ding, Y. 2020. The Bamboo Flowering Cycle Sheds Light on Flowering Diversity. *Frontiers in Plant Sci.* 11: 495867.

Zhou, G., Guan, L., Wei, X., Zhang, D., Zhang, Q., Yan, J., Wen, D., Liu, J., Liu, S., Huang, Z., and Kong, G. 2007. Litterfall production along successional and altitudinal gradients of subtropical monsoon evergreen broadleaved forests in Guangdong, China. *Plant Ecol*. 188: 77-89.

LITTER DYNAMICS AND SOIL CHANGES UNDER SIX-YEAR-OLD BAMBOO STANDS

by

VIJAY KUMAR

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ABSTRACT OF THE THESIS

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DEPARTMENT OF SILVICULTURE AND AGROFORESTRY
COLLEGE OF FORESTRY
KERALA AGRICULTURAL UNIVERSITY
VELLANIKKARA
THRISSUR, KERALA, 680 656

2023

ABSTRACT

Kerala is recognized as a significant biodiversity hub for bamboo species. The state is home to 28 different bamboo species, covering an extensive area of 0.24 million hectares. Despite this rich biodiversity, the total availability of bamboos from both forests and homesteads amounts to only 0.304 million tonnes, falling short of the required 0.62 million tonnes. Though there are some information regarding the growth performance of economically important bamboo species, which are among the designated priority species by INBAR, their effects on improving the site productivity by altering the physicochemical and biological properties of the soil are very much lacking. Moreover, there are some perceived thoughts that litter of bamboos are making impediments rather than improving the soil. In this backdrop, the investigation entitled “Litter dynamics and soil changes under six-year-old bamboo stands” was undertaken in an existing bambusetum at College of Forestry during the period 2022-23. The study aimed to observe the growth behaviour, litter production pattern and nutrient turnover under six different bamboo species viz., *Bambusa vulgaris* Schrad, *Bambusa balcooa* Roxb., *Bambusa tulda* Roxb., *Dendrocalamus brandisii* (Munro) Kurz., *Dendrocalamus asper* (Schult.f.) Back.ex Heyne and, *Dendrocalamus longispathus* Kurz. Changes in soil physico-chemical and biological properties were also assessed over a period of one year.

In terms of growth performance, *Dendrocalamus brandisii* stood out with the highest clump height (14.95m) and internodal length (44.01cm); For culm girth and clump circumference, *Bambusa vulgaris* shown highest value (22.21cm, 6.47m) closely followed by *Dendrocalamus brandisii*, while *Bambusa tulda* showed relatively poor performance in these parameters. However, in number of culms per clump *Dendrocalamus asper* recorded highest closely followed by *Bambusa tulda*.

Litter production varied substantially among different bamboo species, with *Bambusa vulgaris* having the highest annual litter production (9.64 Mg ha^{-1} year^{-1}), while *Bambusa balcooa* exhibited the lowest (6.98 Mg ha^{-1} year^{-1}). Litterfall followed a bimodal distribution pattern, with the major peak occurring after N-E monsoon, during the winter and a minor peak during S-W monsoon. The major composition of litter primarily consisted of leaf, accounting for over 70% of total litterfall, followed by twigs

and sheath. During litter decomposition, a three-phase decomposition pattern was observed for all species. Mass loss of litter samples followed a negative exponential relationship. Notably, species with higher initial nitrogen concentrations, such as *Bambusa tulda*, showed rapid decomposition rates. The decay rate coefficient varied among species, with *Bambusa tulda* having the highest decay rate coefficient (0.292 $month^{-1}$), and *Bambusa balcooa* the lowest (0.123 $month^{-1}$).

Amongst soil physico-chemical and biological properties, *Bambusa balcooa* exhibited higher soil organic carbon content, porosity, and lower bulk density at the topsoil compared to open field conditions. The availability of nutrients like nitrogen, phosphorus, and potassium varied significantly among species, with higher contents being observed under *Dendrocalamus longispathus.* For biological properties also, the *Dendrocalamus longispathus* displayed the highest microbial population with greater accounts from the fungal population while open showed the lowest. Bacterial population varied substantially between species and sampling periods. Dehydrogenase activity was observed highest in the *Bambusa tulda* while lowest under bamboo less control.

The present research findings, provide valuable and quantitative insights into six important bamboo species in terms of their growth performance, litter dynamics, and role in improving physicochemical, and biological properties of soil. The generated data from the current study will help to enumerate the ecological and environmental implications of bamboo cultivation and would serve as a basis for various managerial interventions in bamboo-based land use practices.