นิพนธ์ต้นฉบับ

วนเกษตรสวนยางพาราที่ปลูกร่วมด้วยไม้เศรษฐกิจให้ปริมาณซากพืชและเร่งการย่อยสลายซากพืชได้ดีกว่าสวนยางพาราเชิงเดี่ยวในภาคใต้ของประเทศไทย

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บทคัดย่อ

ที่มาและวัตถุประสงค์: สวนยางพาราเชิงเดี่ยวได้เข้ามาแทนที่ป่าดิบชื้นเขตร้อนเป็นบริเวณกว้างทั่วภูมิภาคเอเชียตะวันออกเฉียงใต้และจีน การขยายตัวอย่างต่อเนื่องของสวนยางพาราในปัจจุบันมีขนาดใหญ่กว่าที่เคยประเมินไว้อย่างมากรวมถึงรุกเข้าไปในพื้นที่ความหลากหลายทางชีวภาพสูง การใช้ที่ดินแบบเข้มข้นนี้ส่งผลกระทบต่อวัฏจักรธาตุอาหารทั้งในกระบวนการผลิตและการย่อยสลายซากพืช อีกทั้งมีส่วนต่อการสูญเสียความหลากหลายของจุลินทรีย์ในดิน อินทรียวัตถุและความสามารถในการกักเก็บน้ำของดิน ซึ่งล้วนเป็นภัยคุกคามต่อผลิตผลระยะยาวของพื้นที่เกษตรกรรมเขตร้อน ระบบวนเกษตรด้วยการปลูกไม้เศรษฐกิจชนิดอื่นร่วมในสวนยางพาราได้ถูกเสนอให้เป็นทางเลือกการใช้ที่ดินที่ยั่งยืน โดยมีรายงานว่าระบบสวนยางพาราแบบผสมผสานมีปริมาณอินทรียวัตถุ ธาตุอาหารที่เป็นประโยชน์ สมบัติทางกายภาพของดินและศักยภาพในการกักเก็บคาร์บอนสูงกว่าสวนยางพาราเชิงเดี่ยว อย่างไรก็ตาม ความเข้าใจเกี่ยวกับอิทธิพลของการปลูกยางพาราร่วมกับไม้เศรษฐกิจต่อพลวัตของซากพืชและวัฏจักรธาตุอาหาร โดยเฉพาะในพื้นที่ที่มีความแตกต่างทางภูมิศาสตร์และภูมิอากาศ ยังมีอยู่อย่างจำกัด การศึกษานี้มีวัตถุประสงค์เพื่อ 1) เปรียบเทียบปริมาณการผลิตซากพืชและอัตราการย่อยสลายซากใบยางพาราระหว่างสวนวนเกษตรยางพาราและสวนยางพาราเชิงเดี่ยวในภาคใต้ของประเทศไทย และ 2) ระบุปัจจัยด้านสิ่งแวดล้อมและภูมิศาสตร์ที่เป็นสาเหตุของความแตกต่างที่พบ

วิธีการ: ดำเนินการเปรียบเทียบปริมาณการผลิตซากพืชและการย่อยสลายซากใบยางพารา เป็นระยะเวลาหนึ่งปี ในพื้นที่สวนวนเกษตรยางพาราและสวนยางพาราเชิงเดี่ยวอายุ 20 ปี จำนวน 3 พื้นที่ ที่แตกต่างกันทางภูมิศาสตร์ของคาบสมุทรภาคใต้ของประเทศไทย โดยสองพื้นที่ตั้งอยู่บริเวณชายฝั่งตะวันออกภาคในอำเภอจะนะและตำบลน้ำน้อย จังหวัดสงขลา และอีกหนึ่งพื้นที่ตั้งอยู่บริเวณชายฝั่งตะวันตก ในตำบลนาโต๊ะหมิง จังหวัดตรัง ซึ่งมีปริมาณน้ำฝนรายปีตลอดช่วงการศึกษาเท่ากับ 2,180 มิลลิเมตร โดยช่วงเวลาของฤดูฝนมีความแตกต่างกันระหว่างสองชายฝั่ง ต้นยางพาราทุกแปลงมีความหนาแน่นใกล้เคียงกัน (375–468 ต้น/เฮกตาร์) ส่วนไม้เศรษฐกิจที่ปลูกแซมในแปลงวนเกษตร ได้แก่ ยางนา (**Dipterocarpus alatus**) กฤษณา (**Aquilaria crassna**) และตะเคียนทอง (**Hopea odorata**) มีอายุ 7–13 ปี และมีพื้นที่หน้าตัดลำต้นรวม 4–12 ตารางเมตร/เฮกตาร์ เก็บตัวอย่างซากพืชที่ร่วงหล่นเป็นรายเดือนด้วยตะแกรงดักซากพืช ขนาด 1 ตารางเมตร

(15 ตะแกรงต่อฟาร์ม รวม 90 ตะแกรง) และประเมินการย่อยสลายของซากใบยางพาราด้วยเทคนิคถุงตาข่ายซากพืช (litterbag) ครอบคลุมทั้งฤดูฝนและฤดูแล้ง นอกจากนี้ยังมีการวัดตัวแปรด้านสิ่งแวดล้อม ได้แก่ อุณหภูมิ ความชื้นสัมพัทธ์ ความหนาแน่นของเรือนยอด และความชื้นในดิน ในแต่ละพื้นที่ เพื่ออธิบายปัจจัยแวดล้อมของระบบการปลูกทั้งสองแบบ

ผลการศึกษา: ปริมาณการผลิตซากพืชในสวนวนเกษตรยางพารามีค่าสูงกว่าสวนยางพาราเชิงเดี่ยวอย่างมีนัยสำคัญทางสถิติ ($p < 0.05$) สม่ำเสมอตลอดทั้งปี โดยปริมาณการผลิตซากพืชรวมรายปีในสวนวนเกษตรและสวนเชิงเดี่ยว เท่ากับ 4.18 ± 0.35 และ 2.56 ± 0.34 เมกะกรัม/เฮกตาร์/ปี ตามลำดับ ซากใบไม้คิดเป็นสัดส่วนประมาณร้อยละ 80 ของปริมาณซากพืชทั้งหมดในทั้งสองระบบ และการปลูกไม้เศรษฐกิจร่วมกับยางพาราช่วยเพิ่มปริมาณซากใบไม้ในสวนวนเกษตรได้ถึงร้อยละ 50 ทั้งสองระบบมีปริมาณการผลิตซากพืชในฤดูแล้งสูงกว่าฤดูฝนอย่างมีนัยสำคัญทางสถิติ (0.34 ± 0.31 และ 0.22 ± 0.21 เมกะกรัม/เฮกตาร์/เดือน ตามลำดับ; $p < 0.001$) โดยชนิดของระบบการปลูกและฤดูกาลต่างมีผลอย่างมีนัยสำคัญและเป็นอิสระต่อกัน โดยไม่มีปฏิสัมพันธ์ระหว่างสองปัจจัยนี้อย่างมีนัยสำคัญ นอกจากนี้ยังพบความแตกต่างทางภูมิศาสตร์ในช่วงเวลาที่มีการผลิตซากพืชสูงสุด กล่าวคือ ปริมาณซากใบยางพาราสูงสุดเกิดขึ้นในเดือนมีนาคมที่พื้นที่ชายฝั่งตะวันออก แต่เกิดขึ้นเร็วกว่านั้นตั้งแต่เดือนมกราคมถึงกุมภาพันธ์ในพื้นที่ชายฝั่งตะวันตก ซึ่งสะท้อนถึงความแตกต่างของช่วงเวลามรสุมตะวันตกเฉียงใต้และมรสุมตะวันออกเฉียงเหนือที่ถูกปรับเปลี่ยนโดยเทือกเขาตะนาวศรี ซึ่งนับเป็นการรายงานความแตกต่างทางภูมิศาสตร์ในช่วงเวลาการร่วงของซากใบยางพาราระหว่างสองฝั่งชายฝั่งภาคใต้ของไทยเป็นครั้งแรก ซากใบยางพารายังย่อยสลายเร็วกว่าอย่างมีนัยสำคัญ ($p < 0.05$) ในสวนวนเกษตรเมื่อเทียบกับสวนเชิงเดี่ยว โดยมีอัตราการย่อยสลายเฉลี่ยรายปีเท่ากับ 6.57 ± 0.45 และ 4.56 ± 0.74 กรัม/ปี ตามลำดับ ระยะเวลาครึ่งชีวิต (t50%) ของซากใบยางพาราในสวนวนเกษตรและสวนเชิงเดี่ยว มีค่าเท่ากับ 0.11 ± 0.01 และ 0.15 ± 0.02 ปี ตามลำดับ ขณะที่ระยะเวลาที่ใช้ในการสูญเสียมวลร้อยละ 95 (t95%) เท่ากับ 0.46 ± 0.03 และ 0.67 ± 0.11 ปี ตามลำดับ ซึ่งบ่งชี้ถึงอัตราการคืนธาตุอาหารสู่ดินที่รวดเร็วกว่าอย่างชัดเจนในระบบวนเกษตร อัตราการย่อยสลายในฤดูแล้งต่ำกว่าฤดูฝนอย่างเห็นได้ชัดในทั้งสองระบบ โดยในสวนวนเกษตรอัตราการย่อยสลายในฤดูฝน (3.98 ± 0.64 กรัม/เดือน) สูงกว่าฤดูแล้ง (0.99 ± 0.18 กรัม/เดือน) ประมาณสี่เท่า ความแตกต่างของอัตราการย่อยสลายระหว่างระบบการปลูกแตกต่างอย่างมีนัยสำคัญทางสถิติในฤดูฝน ($p < 0.01$) แต่ไม่มีนัยสำคัญในฤดูแล้ง ($p > 0.05$) ซึ่งบ่งชี้ว่าสภาพภูมิอากาศเฉพาะที่ (microclimate) ที่เอื้ออำนวยของสวนวนเกษตรมีความสำคัญต่อกิจกรรมของผู้ย่อยสลายในช่วงฤดูฝน นอกจากนี้ สวนวนเกษตรมีปัจจัยแวดล้อมอื่น ๆ ที่สูงกว่าสวนเชิงเดี่ยว ทั้งความชื้นสัมพัทธ์ ($86.61 \pm 7.37\%$ เทียบกับ $75.66 \pm 8.97\%$) ความหนาแน่นของเรือนยอด ($89.67 \pm 7.96\%$ เทียบกับ $59.97 \pm 5.59\%$) และความชื้นในดิน ($3.90 \pm 0.64\%$ เทียบกับ $2.00 \pm 0.86\%$)

สรุป: ระบบวนเกษตรยางพาราแบบผสมผสานกับไม้เศรษฐกิจช่วยเพิ่มทั้งปริมาณซากพืชและอัตราการย่อยสลายเมื่อเทียบกับสวนยางพาราเชิงเดี่ยว ส่งผลให้เกิดการคืนธาตุอาหารสู่ดินในปริมาณที่มากขึ้นและสม่ำเสมอมากขึ้นตลอดทั้งปี อัตราการย่อยสลายที่สูงขึ้นในสวนวนเกษตรน่าจะเป็นผลมาจากสภาพ

ภูมิอากาศเฉพาะที่ที่เอื้ออำนวยมากกว่า ได้แก่ โครงสร้างเรือนยอดที่ซับซ้อนและหนาแน่นกว่า ความชื้นสัมพัทธ์ที่สูงกว่า และความชื้นในดินที่มากกว่า ประกอบกับกิจกรรมทางชีวภาพของจุลินทรีย์และสัตว์หน้าดินในดินที่เพิ่มขึ้นจากความหลากหลายของซากพืชที่มากกว่า นอกจากนี้ ปริมาณซากพืชปกคลุมผิวดินที่มากขึ้นในสวนวนเกษตรยังอาจช่วยลดผลกระทบจากฝนตกหนักต่อผิวดิน จึงช่วยบรรเทาการชะล้างพังทลายของดินได้อีกทางหนึ่ง จากสถานการณ์การขยายตัวของสวนยางพาราในภูมิภาคเอเชียตะวันออกเฉียงใต้ที่ยังคงดำเนินต่อไปและมักถูกประเมินต่ำกว่าความเป็นจริง ผลการศึกษานี้สนับสนุนการส่งเสริมระบบวนเกษตรยางพาราแบบผสมผสานกับไม้เศรษฐกิจให้เป็นแนวทางการใช้ที่ดินที่ยั่งยืนทางนิเวศวิทยามากกว่าสวนยางพาราเชิงเดี่ยวแบบดั้งเดิม

คำสำคัญ: ระบบเกษตรกรรม วนเกษตร ซากใบไม้ สวนยางวนเกษตร การหมุนเวียนธาตุอาหาร

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ORIGINAL ARTICLE

Rubber-timber Tree Agroforests Produce Greater Litter and Enhance Litter Decomposition more than Rubber Monocultures in Southern Thailand

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ABSTRACT

Background and Objectives: Rubber monoculture has replaced large areas of tropical rain forest across Southeast Asia and China, and its continued expansion is now recognized to be substantially greater than previous estimates, including within Key Biodiversity Areas. This intensive land use impairs nutrient cycling by disrupting litter production and decomposition, and is further associated with declining soil microbial diversity, depleted soil organic matter, and reduced water retention capacity, all of which threaten the long-term productivity of tropical agricultural landscapes. Agroforestry, which integrates timber or other tree species into rubber plantations, has been proposed as a more sustainable land-use alternative, and prior work has linked diversified rubber systems to higher soil organic matter, greater nutrient availability, improved soil physical quality, and higher carbon sequestration potential relative to monocultures. However, how rubber-timber intercropping specifically influences litter dynamics and nutrient cycling, particularly across geographically and climatically distinct regions, remains poorly understood. This study aimed to compare litter production and rubber leaf litter decomposition rates between rubber agroforests and monocultures in southern Thailand, and to identify the environmental and geographical factors underlying observed differences.

Methodology: Litter production and rubber leaf litter decomposition were compared over one year across three sites of 20-year-old para rubber agroforest and monoculture farms in southern Thailand. Two sites were located on the eastern coast of peninsular Thailand, in the Chana district and Namnoi subdistricts of Songkhla province, and other was located on the western coast in Na Toh Ming subdistrict of Trang province, allowing comparison across geographically distinct monsoon regimes; annual rainfall during the study period was about 2,180 mm, with rainy-season timing differed between coasts. All sites were similar on para rubber density (375–468 individuals ha^{-1}); intercropped timber species (**Dipterocarpus alatus**, **Aquilaria crassna**, and **Hopea odorata**) were 7–13 years old with a total basal area of 4–12 m^2 ha^{-1}. Litterfall was collected monthly using 1 m^2 litter traps (15 per farm, 90 total), and rubber leaf litter decomposition was assessed using the litterbag technique across both the rainy and dry seasons. Environmental variables, including temperature, relative humidity, canopy cover, and soil moisture, were also measured at each site to help explain observed differences in litter dynamics between farm types.

Main Results: Litter production was consistently higher in rubber agroforests than in rubber monocultures throughout the year. Total annual litter production was significantly different ($p < 0.05$) between rubber practices;

4.18 ± 0.35 Mg ha^{-1} yr^{-1} in agroforests, and 2.56 ± 0.34 Mg ha^{-1} yr^{-1} in monocultures. Leaf litter contributed approximately 80% of total litter production in both systems, and intercropped timber trees contributed roughly 50% more leaf litter to agroforests. In both systems, litter production was greater during the dry season than the rainy season (0.34 ± 0.31 vs. 0.22 ± 0.21 Mg ha^{-1} mo^{-1}; $p < 0.001$), with farm type and season each having significant, independent effects and no significant interaction between them. Geographical variation in the timing of peak litter production was also observed: peak leaf litter production occurred in March at the eastern sites but as early as January–February at the western site, reflecting differences in the timing of the southwest and northeast monsoons as modulated by the Tenasserim mountain range—apparently the first documented evidence of such geographical variation in rubber leaf litterfall timing between the two coasts of southern Thailand. Rubber leaf litter also decomposed significantly ($p < 0.001$) faster in agroforests than in monocultures, with mean annual decomposition rates of 6.57 ± 0.45 g yr^{-1} versus 4.56 ± 0.74 g yr^{-1}. The half-life of rubber leaf litter (t50%) was 0.11 ± 0.01 year in agroforests versus 0.15 ± 0.02 year in monocultures, while the time required for 95% mass loss (t95%) was 0.46 ± 0.03 versus 0.67 ± 0.11 year, indicating substantially faster nutrient return in agroforestry systems. Decomposition rates were markedly lower during the dry season than the rainy season in both systems; in agroforests, rainy-season decomposition (3.98 ± 0.64 g mo^{-1}) was approximately four times higher than dry-season rates (0.99 ± 0.18 g mo^{-1}). The difference in decomposition rates between farm types was significant during the rainy season ($p < 0.01$) but not the dry season ($p > 0.05$), suggesting that the favorable microclimate of agroforests is particularly important for decomposer activity during the wet period. Agroforests also had significantly higher in all environments than monoculture, for instant, relative humidity (86.61 ± 7.37% vs. 75.66 ± 8.97%), canopy cover (89.67 ± 7.96% vs. 59.97 ± 5.59%), and soil moisture content (3.90 ± 0.64% vs. 2.00 ± 0.86%).

Conclusion: Rubber-timber agroforestry enhances both litter quantity and decomposition dynamics relative to rubber monoculture, providing greater and more consistent annual nutrient returns to the soil. The higher decomposition rates observed in agroforests are likely driven by more favorable microclimatic conditions, dense crown canopy, high relative humidity and soil moisture content—together with enhanced biological activity of soil microbes and macrofauna promoted by more diverse litter inputs. The greater litter cover in agroforests may also help reduce the impact of heavy rainfall on the soil surface, thereby mitigating erosion. Given the ongoing and often underestimated expansion of rubber plantations across Southeast Asia, these findings support the promotion of rubber-timber agroforestry as a more ecologically sustainable land-use practice than conventional rubber monoculture.

Keywords: Agricultural systems, agroforest, leaf litter, rubber agroforestry, nutrient cycling

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Introduction

Cash crop plantations such as oil palm and para rubber are responsible for large-scale forest clearance in tropical countries (Stibig **et al.**, 2014). Para rubber (**Hevea brasiliensis** Müll. Arg.) is a major economic tree crop in tropical regions, particularly in Southeast Asia (Kumagai **et al.**, 2014). More than 1,500,000 ha of land are estimated to have been converted to rubber plantation in southern China, Thailand, Vietnam, and Cambodia during 2003 to 2010 (Association of Natural Rubber Producing Countries [ANRPC], 2010). Recent satellite mapping indicates that para rubber related forest loss in Southeast Asia has been substantially underestimated, with deforestation at least two to three times higher than previous policy estimates, and over one million hectares of plantations established within Key Biodiversity Areas (Ahrends **et al.**, 2023).

The negative effects of monoculture plantations on ecosystems include biodiversity loss, environmental degradation, and reduction in biomass carbon (Wu **et al.**, 2001; Mann, 2009; Qiu, 2009). Para rubber monoculture plantations exemplify these broader ecological impacts, as their continued expansion has been linked to declining soil quality and biological diversity. Specifically, long-term rubber monocultures have been shown to reduce soil microbial and plant diversity, resulting in soil degradation and diminished water retention capacity (Chen **et al.**, 2017; Hong **et al.**, 2024; Liu **et al.**, 2024). Monoculture practices often deplete soil nutrient reserves over time due to the accelerated mineralization of soil organic matter, increased soil erosion, and continuous nutrient export through latex harvesting (Kittitornkool **et al.**, 2019; Hua **et al.**, 2021). Impaired nutrient cycling is another important negative consequence of para rubber monoculture. However, our understanding of the ecological process underlying nutrient cycling in rubber plantations remains limited. Litter fall and litter decomposition are key mechanisms for transferring nutrients to the soil. They play crucial roles in regulation of nutrient cycling and primary productivity, as well as in maintaining soil fertility in terrestrial ecosystems (Olson, 1963; Aerts & Caluwe, 1997; Prescott, 2004; Shiels, 2006). Land use change associated with cultivation and agricultural practice can rapidly degrade soil quality (Islam & Weil, 2000). Therefore, understanding nutrient cycling in agricultural systems is vital, as plant productivity depends on maintaining this nutrient balance (Ouédraogo **et al.**, 2001).

For ecosystem sustainability, managed land use should imitate the structure and functioning of natural ecosystems (Ewel, 1999). Agroforestry is a land use management practice that enhances productivity and sustainability of farming systems by integrating agriculture and forestry into a single system (Nair, 1998). Recent studies highlight the substantial benefits of rubber agroforestry systems for soil health and overall ecosystem services. Integrating para rubber with diverse plant species significantly enhances soil organic matter, cation exchange capacity, and essential nutrients such as nitrogen, potassium, calcium, and magnesium compared to monoculture systems (Tongkaemkaew **et al**., 2025). Moreover, the diversified plant cover in rubber agroforests creates suitable ecological niches that enhance soil microbial communities, which play crucial roles in nutrient cycling and long-term soil fertility (Hua **et al**., 2021; Wen **et al**., 2022). Intercropping rubber with native trees has also been shown to increase soil porosity and reduce bulk density, further improving physical soil quality (Qi **et al**., 2025). Studies on litterfall in rubber intercropping systems have consistently found that annual litterfall biomass and associated carbon and nutrient returns are substantially higher in agroforestry than in rubber monoculture, with nutrient returns 1.3–1.6 times greater in diversified systems (Bai **et al**., 2024; Qi **et al**., 2024).

In terms of climate change mitigation, rubber agroforestry also exhibits higher potential for total ecosystem carbon sequestration and storage than monoculture plantations (Besar **et al**., 2020). While the traditional adoption of agroforestry systems in Thai rubber farms has been relatively small-scale, there is a growing movement among smallholder farmers in southern Thailand to form networks and adopt rubber agroforestry practices to increase their resilience against economic and climate variability (Kittitornkool **et al**., 2019). These farmers integrate timber, fruit trees, or native species between rows of rubber trees, resulting in greater plant diversity and canopy complexity (Somboonsuke **et al.**, 2011; Kittitornkool **et al**., 2019). The multiple canopy layers and dense undergrowth in rubber agroforestry effectively reduce surface runoff and soil erosion from heavy rainfall, providing a variety of economically valuable secondary products to farmers (Kittitornkool **et al**., 2019; Hua **et al**., 2021).

Although recent studies have begun to explore litterfall and decomposition dynamics in rubber agroforestry systems in southern Thailand (Tongkaemkaew **et al**., 2018), litter dynamics in rubber–timber agroforestry systems across the contrasting climatic regions of the east and west coasts of the southern Thai peninsula have not been comprehensively evaluated. Therefore, the present study aims to compare litter production and rubber leaf litter decomposition rates between rubber-timber tree agroforests and monocultures. We hypothesize that litter production would be greater and that leaf litter would decompose more rapidly in rubber agroforestry systems than in monoculture. We hypothesize that litter production would be greater and that leaf litter would decompose more rapidly in rubber agroforestry systems than in rubber monoculture.

We also hypothesized that litter production would differ between the eastern and western coasts of the southern Thai peninsula. The findings of this study provide insights into the role of rubber agroforestry in enhancing nutrient cycling and contribute to the evaluation of its sustainability relative to rubber monoculture systems.

Materials and Methods

1. Study sites

The study was conducted in three pairs of rubber agroforests and rubber monocultures in southern Thailand. Two pairs were located on the eastern coast of peninsular Thailand, in Chana district (6°55′59.7″N 100°40′08.5″E) and Namnoi (7°04′08.0″N 100°31′31.1″E) subdistricts of Songkhla province, while one pairs was located on the western coast in Na Toh Ming subdistrict (7°33′12.04″N 99°30′38.8″E) of Trang province, west coast (Table 1).

The annual rainfall during study period, from January to December 2013, was 2,180 mm. The region experiences two main seasons, which vary somewhat in timing between the western and eastern coasts peninsula. On the western coast, the rainy season occurs from May to October, whereas on the eastern coast it extends from August to January, based on ten years (2005 to 2014) of rainfall data. The main dry season occurs from mid-February to mid-April. The average monthly temperature is low from October to December at 26.7 ºC and peak in April at 28.6 ºC.

Table 1. Environmental variables measured at each study site

Study sites	Mean			Soil properties					
	RH (%)	AAT (°C)	RF (mm yr^{1})	Texture	pH	OM (%)	OC (%)	TN (%)	SMC (%)
Rubber agroforest									
-Chana district	90.98	26.81	1,463.5	SL	7.35	0.97	0.57	0.06	3.2
-Namnoi subdistrict	88.52	27.33	1,960.7	SL	4.13	1.78	1.04	0.08	4.0
-Na toh ming subdistrict	80.33	27.56	2,024.8	SL	3.93	1.55	0.90	0.07	4.5
Rubber monoculture									
-Chana district	79.69	27.45	1,463.5	SL	6.28	0.74	0.74	0.05	1.2
-Namnoi subdistrict	77.35	28.04	1,960.7	SL	4.41	1.24	0.72	0.07	2.0
-Na toh ming subdistrict	69.95	28.16	2,024.8	SL	3.75	1.53	0.89	0.08	2.9

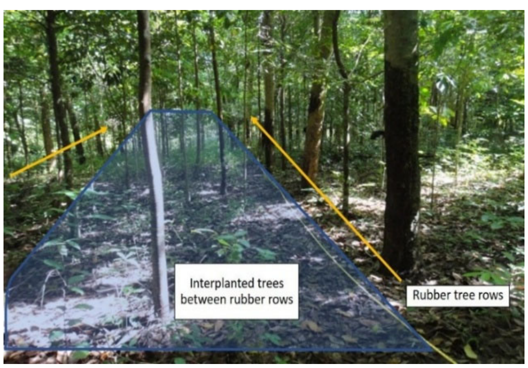
Remarks: RH = relative humidity, AAT = annual air temperature, RF = rainfall, OM = organic matters, OC = Organic carbon, TN = total nitrogen, SMC = soil moisture content at 30 cm depth, and SL = sandy loam.

2. Data collection

1) In each study site, a pair of rubber agroforest and rubber monoculture located close to each other (mean± SD = 30 ± 5 m) was selected to control soil characteristics and groundwater content. These farms were converted from

primary forest more than 70 years ago and are currently in the third rubber planting cycle. The rubber trees in all sites were of similar age, approximately 20 years old, with densities ranging from 375 to 468 individuals ha^{-1}. The average basal area of rubber trees was 33.5 ± 5.6 m^2 ha^{-1} in rubber agroforests (Chana: 28.94, Namnoi: 39.78, and Na toh ming: 31.72 m^2 ha^{-1}) and 28.1 ± 5.4 m^2 ha^{-1} in rubber monoculture (Chana: 33.82, Namnoi: 22.98, and Na toh ming: 27.53 m^2 ha^{-1}). The study sites were predominantly surrounded by rubber plantations. Almost all rubber trees across the six plots were the same commercial clone (RRIM 600), which is the dominant cultivar planted in southern Thailand, so clonal/phenological differences between sites are minimal. The rubber agroforest plot in Namnoi subdistrict, Songkhla province is the only one that has BMP 24 clone.

In the rubber agroforests, timber species were planted between the rows of rubber trees, and in one farm, they were planted both between and within rubber tree rows (Figure 1A and 1B). The timber species included **Dipterocarpus alatus**, **Aquilaria crassna**, and **Hopea odorata**. These tree species were 7 to 13 years old, with a total basal area ranging from 4 to 12 m^2 ha^{-1} (Chana: 12.53, Namnoi: 5.61, and Na toh ming: 4.09 m^2 ha^{-1}) and a density of 400 to 1,200 individuals ha^{-1}. While, in rubber monocultures, the ground was covered only by short grass during the non-tapping period in the late dry season from February to May.



(A)


(B)

Figure 1 Twenty-year-old rubber agroforest (A) and rubber monoculture (B) in Namnoi subdistrict, Songkhla province.

2) A mixture of ten soil samples from each study site was collected and analyzed for soil properties at the Central Analytical Center, Faculty of Natural Resources, Prince of Songkla University in Hat Yai, Thailand. The soil texture across all sites was sandy loam. In rubber agroforests, the average soil pH was 5.13 ± 1.92, soil organic matter was 1.43 ± 0.42 percent, total nitrogen was 0.07 ± 0.01 percent, and organic carbon was 0.84 ± 0.24 percent. In rubber monocultures, the average soil pH was 4.81 ± 1.31, soil organic matter was 1.17 ± 0.40 percent, total nitrogen was 0.07 ± 0.02 percent, and organic carbon was 0.78 ± 0.09 percent (Table 2).

Table 2. Soil properties (Mean ± SD and range) in rubber agroforestry and rubber monoculture systems

Soil property	Para rubber agroforest	Para rubber monoculture	**F** value	**p** value
pH	5.13 ± 1.92 (3.93–7.35)	4.81 ± 1.31 (3.75–6.28)	-0.241	0.823
Organic matter (%)	1.43 ± 0.42 (0.97–1.78)	1.17 ± 0.40 (0.74–1.53)	-0.789	0.474
Organic carbon (%)	0.84 ± 0.24 (0.57–1.04)	0.78 ± 0.09 (0.72–0.89.)	-0.357	0.748
Total nitrogen (%)	0.07 ± 0.01 (0.06–0.08)	0.07 ± 0.02 (0.05–0.08)	-0.316	0.770

3) Litter fall was collected using litter traps with an area of 1 m^2. Fifteen traps were placed randomly at 1 m above ground in each farm, resulting in a total of 90 traps across all studied sites. Each trap consisted of a PVC frame with 1 mm nylon mesh netting. Litter was collected monthly over one year and oven dried at 60 to 70 ºC for 48 hours. All samples were separated into leaves, branches, fruits and flowers, and weighed using a digital scale.

4) Decomposition rate across farm types were measured using a litterbag technique. Litterbags measuring 20 cm by 20 cm were made from 1 mm nylon mesh, and a 1 cm^2 opening was created on each of two sides to allow access by macroinvertebrates (Barlow et al., 2007). Each litterbag was filled with 6 grams of oven dried rubber leaves collected from the plantation. At each study site, 90 litterbags were placed systematically on the soil surface at the end of December 2012 for the dry season treatment, and a second set of 90 litterbags was deployed at the end of September 2013 for the rainy season treatment. Subsequently, six litterbags were collected monthly from each study site and transported to the laboratory. Soil particles were removed from the litter, and samples were oven dried at 60 to 70 ºC for 48 hours. Data was collected for 12 months.

5) Environmental measurement

The temperature and relative humidity were measured hourly using data loggers (Tenmars, Model: TM-305U) installed at 1.5 m above the ground from January to December 2013. Soil moisture content (SMC) was determined from ten randomly collected samples in each site. SMC was measured monthly from June 2013 to May 2014, with all measurements consistently taken between 09:00 and 10:00 AM. Canopy cover percentage was estimated using a densiometer at five sampling points per plot, including the center and each corner, within three 30 m × 30 m plots at each farm.

3. Data analysis

1) The decomposition rates coefficient k was calculated from the decay curve using the following equation:

$$\ln(M_0 / Mt) = \mathbf{k} \cdot t$$

where M_0 represents the initial litter mass, M_t represents the remaining mass at a certain time t, t is the amount of time passed since the initial measurement, and **k** is the decomposition constant. Following Olson (1963), the time required to decompose 50% ($t_{50\%}$) and 95% ($t_{95\%}$) of the litter mass is 0.693/**k**, and = 3/**k**, respectively.

2) Statistical analysis

2.1) To evaluate monthly leaf litter production across three study sites and two farming systems (monoculture vs. agroforest), a statistical of three-way repeated-measures factorial model (System x Site x Month) was evaluated in R. Initial linear mixed-effects model diagnostics showed that residuals violated normality (Shapiro-Wilk test, $p < 0.05$) despite satisfying homogeneity of variance (Levene's test, $p < 0.05$). Consequently, an Aligned Rank Transform (ART) ANOVA was conducted using the ARTool package, specifying plot identity (Plot_ID) as a random intercept to account for temporal autocorrelation across the 12 sampling months. Main effects and interaction terms were evaluated using Type III ANOVA tables. Significant interaction terms were further analyzed via post-hoc pairwise contrasts to compare (1) land-use systems within each month and site combination and (2) study sites within each system and month combination using the emmeans package, with **p**-values adjusted using Tukey's HSD method ($\alpha = 0.05$).

2.2) For litter decomposition, a generalized linear mixed model (GLMM) was applied using the lme4 package, with decomposition rate as dependent variables, since decomposition rate (**k**) did not show a normal distribution after a normality test (Shapiro-Wilk test) was applied. To examine the effect of farm type on decomposition rate, farm type was treated as a fixed effect, while study sites and traps were included as random effects. To assess the effect of season on decomposition rate, repeated measures general linear model (GLM) was used. A t-test was applied to compare mean monthly temperature, relative humidity, canopy cover, and soil moisture content between farm types. All statistical analyses were conducted using R program (R Development Core Team version 3.2.0, http://www.R-project.org). Data are presented as mean ± SD throughout.

Results

1. Litter fall

The total annual litter fall in rubber agroforests was 4.18 ± 0.35 Mg ha^{-1} yr^{-1}, which was significantly higher than that in rubber monocultures, 2.56 ± 0.34 Mg ha^{-1} yr^{-1}. The GLMM results showed that farm type significantly affected litter production ($F = 64.72$, $df = 1$, $p < 0.001$). Litter production was higher in every month in rubber agroforests compared to rubber monocultures (Table 3 and 4).

The leaf fraction contributed the largest proportion, accounting for approximately 80% of total litter production. Mean monthly rubber leaf litter in rubber agroforests, 0.20 ± 0.02 Mg ha^{-1} mo^{-1}, was comparable to that in rubber monocultures, 0.17 ± 0.06 Mg ha^{-1} mo^{-1}. Rubber agroforests had approximately 50% greater leaf litter input from intercropped plant species, 0.11 ± 0.04 Mg ha^{-1} mo^{-1}. Other litter fractions, including branches, fruits and flowers, contributed similarly in both farms. In rubber agroforests, branch, fruit, and flower litter production was 0.02 ± 0.01, 0.02 ± 0.01, and 0.01 ± 0.01 Mg ha^{-1} mo^{-1}, respectively, while in rubber monocultures the corresponding values were 0.03 ± 0.01, 0.01 ± 0.01, and 0.02 ± 0.01 Mg ha^{-1} yr^{-1}, respectively (Table 3).

Table 3. Litter production (mean ± SD) in rubber agroforests and rubber monocultures

Litter production	Rubber agroforest	Rubber monocultures
Total annual litter fall (Mg ha^{-1} yr^{-1}) *	4.18 ± 0.35	2.56 ± 0.34
Rubber leaf litter (Mg ha^{-1} mo^{-1})	0.20 ± 0.02	0.17 ± 0.06
Branch litter (Mg ha^{-1} mo^{-1})	0.02 ± 0.01	0.03 ± 0.01
Fruit litter (Mg ha^{-1} mo^{-1})	0.02 ± 0.01	0.01 ± 0.01
Flower litter (Mg ha^{-1} mo^{-1})	0.01 ± 0.01	0.02 ± 0.01

* Indicate statistically significant differences between the two farm types.

Table 4. Pairwise comparisons between rubber agroforest and rubber monoculture by month and site.

Rubber agroforest VS. Rubber monoculture	Site 1 Chana subdistrict	Site 2 Namnoi subdistrict	Site 3 Na toh ming subdistrict
January	t = 9.521, **p** < 0.0001	t = 1.495, **p** = 0.1354	t = -8.798, **p** < 0.0001
February	t = -9.381, **p** < 0.0001	t = -6.035, **p** < 0.0001	t = 8.723, **p** < 0.0001
March	t = -5.245, **p** < 0.0001	t = 8.091, **p** < 0.0001	t = -7.594, **p** < 0.0001
April	t = -1.157, **p** = 0.2477	t = 8.188, **p** < 0.0001	t = -7.849, **p** < 0.0001
May	t = 3.736, **p** = 0.002	t = -1.805, **p** = 0.0715	t = -2.740, **p** = 0.0063
June	t = -1.643, **p** = 0.1009	t = 0.478, **p** = 0.6330	t = 1.172, **p** = 0.2418
July	t = 0.983, **p** = 0.3259	t = -3.278, **p** = 0.0011	t = 1.789, **p** = 0.0741
August	t = -5.791, **p** < 0.0001	t = -7.824, **p** < 0.0001	t = 6.851, **p** < 0.0001
September	t = 3.152, **p** = 0.0017	t = -3.611, **p** = 0.0003	t = 0.117, **p** = 0.9069
October	t = 4.623, **p** < 0.0001	t = -3.807, **p** = 0.0002	t = -1.419, **p** = 0.1565
November	t = 0.086, **p** = 0.9314	t = -2.970, **p** = 0.0031	t = 3.070, **p** = 0.0022
December	t = -5.273, **p** < 0.0001	t = -0.437, **p** = 0.6622	t = 5.629, **p** < 0.0001

Although litter production occurred throughout the year in both farm types, it was proportionally greater during the dry season, 0.34 ± 0.31 Mg ha^{-1} mo^{-1}, than during the rainy season, 0.22 ± 0.21 Mg ha^{-1} mo^{-1}. The GLM result indicated significant effects of both season and farm type on rubber leaf litter production (**F**=72.80 and **F**=97.28, df = 1, **p** < 0.001), with no interaction between the two factors (**F**=0.98, df=1, **p** = 0.32).

Geographical variation in the temporal pattern of rubber leaf litter production was recognized between the eastern sites, Namnoi and Chana subdistrict in Songkhla province and the western site, Na toh ming in Trang province. In the eastern coast, peak rubber leaf litter production generally occurred in the middle of the dry season, in March, except in the rubber agroforest at Chana subdistrict, where it peaked in January (Figure 2). On the western coast, rubber litter fall also peaked during the dry season, occurring earlier, between January-February (Figure 2). In some cases, irregular patterns occurred such as in Na toh ming subdistrict. Leaf shedding their peaks earlier (January-February) during the west-coast dry period, while the August rise corresponds to storm-driven litterfall at the middle of the west-coast rains. Litter production of other fractions showed intermittent patterns. Branch litter fall exhibited two peak periods, while flower litter fall occurred once per year. Fruit litter production occurred twice annually in rubber agroforests but only once in rubber monocultures. Indicates statistically significant differences between the two sites.

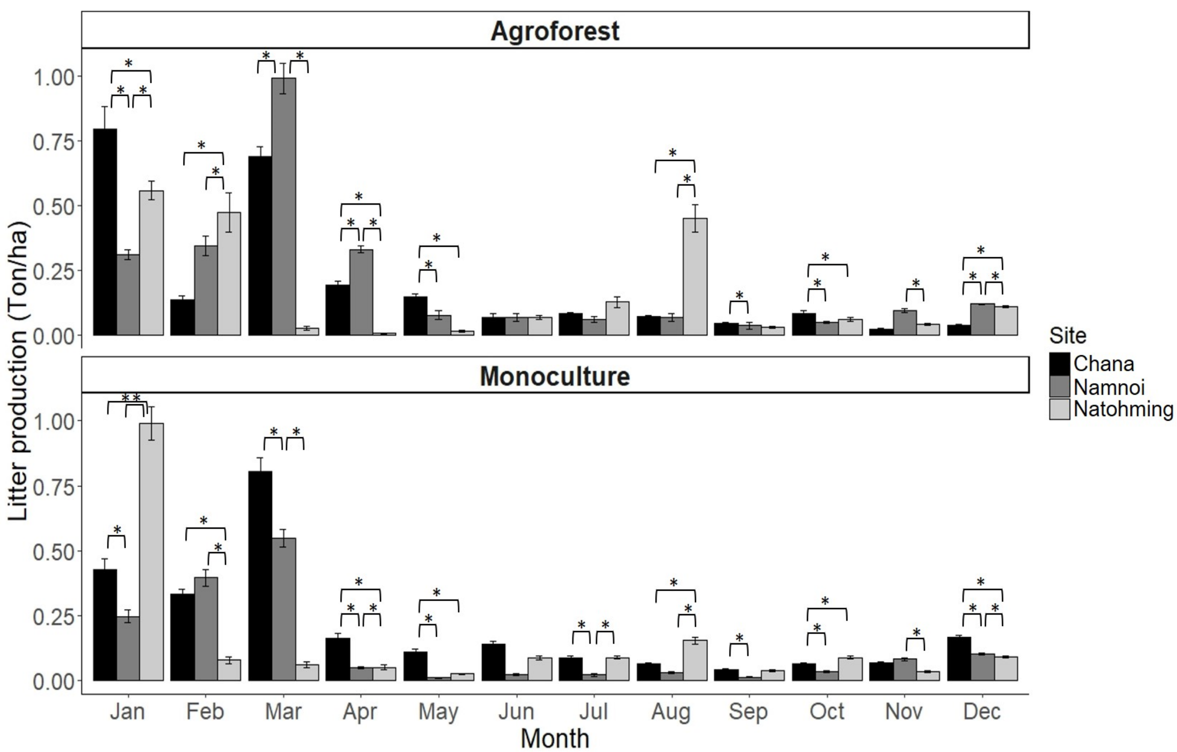


Figure 2. Rubber leaf litter (Mg ha^{-1}) in each study site in rubber agroforest and rubber monoculture.

* Indicates statistically significant differences between the two sites.

2. Rubber leaf decomposition

Generally, rubber leaves decompose gradually and are almost completely degraded within one year. The remaining litter mass after one year was lower in rubber agroforests, ranging from 0.08–0.19 %, than in rubber monocultures ranging from 0.80–2.40%. Mean decomposition rates were higher in rubber agroforests, 6.57 ± 0.45 g yr^{-1}, than in rubber monocultures, 4.56 ± 0.74 g yr^{-1}. Farm type had a highly significant effect on the decomposition rate (**F** = 26.87, df = 1, **p** < 0.001). The half-life ($t_{50\%}$) in rubber agroforests and monocultures was 0.11 ± 0.01 and 0.15 ± 0.02 year, respectively. The time required for 95% mass loss ($t_{95\%}$) in rubber agroforests and monocultures was 0.46 ± 0.03 and 0.67 ± 0.11 year, respectively.

Decomposition rates were significantly faster during the rainy season than the dry season in both farm types. Season had a highly significant effect on the decomposition rate (**F** = 102.41, df = 1, **p** < 0.001). In rubber agroforests, decomposition rates were 3.98 ± 0.64 g/month with a range of 3.36–4.65 in the rainy and 0.99 ± 0.18 g/month with a range of 0.85–1.19 in the dry season. Similarly, in rubber monocultures, decomposition rates were 2.79 ± 0.48 g/month in the rainy season and 0.91± 0.28 g/month in the dry season. There was a significant difference in decomposition rates between farm types during the rainy season (F = 8.84, df = 1, **p** < 0.05), but no significant difference was observed during the dry season (F = 0.08, df = 1, **p** > 0.05).

3. Environmental variables

Temperature in rubber agroforests, 27.66 ± 0.85 ºC, was slightly lower than in rubber monocultures, 27.89 ± 1.57 ºC, but the difference was not significant (Table 5). In contrast, relative humidity was significantly (**p** < 0.05) higher in rubber agroforests than in rubber monocultures, 86.61 ± 7.37 % and 75.66 ± 8.97 %, respectively. Canopy cover was also significantly (**p** < 0.01) greater in rubber agroforest than rubber monocultures, 89.67 ± 7.96%, and 59.97 ± 5.59%, respectively. Similarly, soil moisture content at a depth of 30 cm was significantly (**p** < 0.05) higher in rubber agroforests than in monocultures, 3.90 ± 0.64 and 2.00 ± 0.86 %, respectively (Table 5).

Table 5. Environmental variables measured in rubber agroforests and monocultures, including statistical tests.

Environmental variables	Rubber agroforest	Rubber monoculture	Statistical value
Temperature (ºC)	27.66 ± 0.8	27.89 ± 1.57	t = -0.77, df = 53.97, **p** = 0.444
Relative humidity (%)	86.61 ± 7.37	75.66 ± 8.97	t = 5.66, df = 67.45, **p** < 0.001
Canopy cover (%)	89.67 ± 7.96	59.97 ± 5.59	t = -5.29, df = 3.59, **p** = 0.008
Soil moisture (%)	3.90 ± 0.64	2.00 ± 0.86%	t = 2.98, **p** < 0.05 **p** = 0.043

Discussion

1. Litter fall

Litter production in rubber agroforests is quantitatively higher than in rubber monocultures. In addition to litter from rubber trees, which occurred mainly during the dry season, litter from intercropped species is added throughout the year. Consequently, rubber agroforests receive greater monthly litter input than rubber monocultures. The higher litter production in rubber agroforests is primarily due to the greater basal area of trees and, potentially, differences in plant composition. This finding is consistent with recent studies from Hainan Island, China, where rubber intercropped with native trees produced greater annual litterfall and higher nutrient returns than rubber monoculture, with temperature and wind speed identified as the dominant climatic drivers of litter dynamics (Qi **et al**., 2024). Similarly, Bai **et al.** (2024) reported that carbon and nutrient returns via litterfall were 1.3–1.6 times higher in rubber agroforestry systems than in monoculture, and litter turnover rates were consistently lower in monoculture across all seasons.

Wang **et al.** (2008) studied litter production in mixed and monocultures of **Cunninghamia lanceolata** in China, where tree density was controlled in both systems. They reported higher litter production in mixed stands than in pure stands, which can be explained by the competitive production principle (Kelty, 2006). According to this principle, differences in physiological and morphological traits among coexisting species allow more complete and efficient utilization of available resources, such as light, water, and nutrients, in mixed-species systems compared with monocultures. Similarly, Gama-Rodrigues **et al**. (2007) reported 29.4% greater biomass in mixed stands compared with pure stands in 22-year-old native tree plantations in Brazil.

In the present study, the higher litter production observed in rubber agroforests compared with rubber monocultures may also be explained by same mechanism. The presence of interplanted tree species likely increases canopy structural complexity and vertical stratification, enhancing light interception and overall resource-use efficiency. In addition, complementary differences in rooting depth and nutrient uptake strategies among species may reduce belowground competition and improve stand-level resource utilization, thereby increasing total biomass production and litter input.

In general, litterfall patterns are influenced by environmental conditions, including temperature, humidity, and soil moisture. In this study, litterfall was concentrated during the dry period, suggesting that seasonal drought stress may play an important role in regulating leaf shedding, as plants respond to reduced water availability (Valenti et al., 2008).

This study is the first, to the best of our knowledge, to demonstrate geographical variation in the litter fall period between the west and east coasts of southern Thailand. The climate and temporal pattern of litter production in this region are significantly influenced by the Asian monsoon and regional geographic processes (Wohlfarth **et al**., 2012; Chabangborn **et al**., 2020; Jirapinyakul **et al**., 2025). This variation is driven by two major monsoons (southwest and northeast monsoons) and the north–south oriented Tenasserim mountain range (Climate center, 2019). The southwest monsoon, which lasts from mid-May to mid-October, brings warm, moist air from the Indian Ocean to the western coast of Thailand, resulting in abundant rainfall. The Tenasserim mountain range blocks this moist air, leading to relatively drier conditions on the eastern coast. In contrast, the northeast monsoon, which occurs from October to January, brings cooler, drier air from mainland China to most of Thailand. However, in southern Thailand, this monsoon carries moisture from the Gulf of Thailand, resulting in milder conditions and substantial rainfall along the eastern coast. The rainy season on the eastern coast typically end in January (Jirapinyakul **et al**., 2025). Therefore, the peak of the rubber leaf fall in the dry season on the west coast begins earlier than on the east coast.

The litter production in this study in rubber agroforest and monocultures, 4.18 and 2.56 Mg $ha^{-1}yr^{-1}$, respectively, falls within the wide range reported for tropical plantations, from 1.02–14.5 Mg $ha^{-1}yr^{-1}$ (Batish **et al**., 2008). Litterfall in primary forests ranges from 9.4–12.4 Mg $ha^{-1}yr^{-1}$, while in secondary forests it ranges from 5.4-13.4 Mg $ha^{-1}yr^{-1}$ (Barlow **et al**., 2007). Litter production in rubber agroforests approaches that of secondary forests as woody trees mature over time.

2. Litter decomposition

The rubber leaf litter decomposition rates observed in the present study are comparable to those reported in a previous study in southern India, which found a rate of 0.013 g day^{-1}, equivalent to 4.75 g yr^{-1} (Jobi, 2006). Overall, the results demonstrate that litter in rubber agroforests decomposes at a faster rate than that in rubber monoculture, and that decomposition occurs more rapidly during the rainy season than during the dry season. The faster decomposition rates in rubber agroforests are closely associated with measured environmental differences between systems, particularly higher soil moisture, higher relative humidity, and greater canopy cover. These conditions likely create a more favorable microclimate by reducing evaporative stress and maintaining more stable moisture conditions, which support litter decomposition. Although microbial biomass, enzyme activity, and soil fauna were not directly measured in this study, previous research suggests that such microclimatic conditions may enhance microbial processes and increase the activity of soil mesofauna and macrofauna, thereby potentially accelerating litter decomposition (; Zhang & Zak, 1995; Bradford **et al**., 2002; Tongkaemkaew **et al**., 2018). However, these mechanisms should be interpreted as indirect explanations rather than direct evidence from this study.

In addition, differences in litter quality between systems may also contribute to decomposition patterns. Mixed-species litter inputs generally exhibit higher heterogeneity in nutrient content, including greater concentrations of essential nutrients (e.g., N, P, and K), more balanced stoichiometric composition, and lower carbon-to-nitrogen (C:N) ratios compared with monoculture litter. These characteristics improve substrate quality and enhance decomposability by providing a wider range of resources for decomposer organisms. However, these effects are inferred from previous studies and were not directly measured in this work (Zhang & Zak, 1995; Liu **et al**., 2024). Season strongly influences litter decomposition rates. In the present study, litter decomposed faster during the rainy season than during the dry season in both farm types, consistent with findings from previous studies in Africa (Ngatia **et al**., 2014). This pattern is likely driven by seasonal variation in rainfall, atmospheric moisture, and radiation, which directly affect soil moisture and decomposer activity. Increased microbial activity and biomass during the rainy season have also been reported in previous studies (Raghubanshi **et al**., 1990). Consequently, higher litter mass loss during the rainy season enhances nutrient release and availability, thereby supporting plant growth and ecosystem productivity (Raghubanshi **et al.**, 1990; Dhanya **et al.**, 2013).

The limited number of rubber agroforests included in this study may constrain the robustness of the conclusions. Future research with a larger number of sites is needed, along with more detailed investigations of biological and environmental parameters, as well as nutrient release during litter decomposition across different species compositions. Rubber agroforests vary in structural complexity and plant diversity; therefore, further studies should examine how these factors influence litter production and decomposition processes. In addition, future work should directly quantify microbial biomass, enzyme activity, soil faunal communities, and litter chemical traits to better resolve the mechanisms underlying decomposition dynamics.

Conclusion

This study finding that rubber agroforests produce more litter and enhance faster decomposition of litter than rubber monocultures. It implies that higher quantity and more regular nutrient returns are added in rubber agroforest than in rubber monoculture in each year. Another crucial ecosystem service provided by rubber agroforests is the effective reduction of soil erosion. The complex, multiple canopy layers of rubber agroforestry, along with extensive understory vegetation and dense leaf litter cover, effectively intercept rainfall and significantly reduce surface runoff and soil erosion on slopes compared to rubber monocultures. It is clear that in the long-term rubber agroforest can maintain soil fertility better than rubber monoculture. As such, a rubber agroforest is a more sustainable agricultural practice in a tropical humid landscape than a rubber monoculture. From a practical management perspective, these findings demonstrate that integrating timber species into rubber plantations can be applied as a highly effective strategy for sustainable land management in tropical landscapes. Because this practice naturally enhances nutrient turnover and soil conservation, it can substantially reduce farmers' reliance on external chemical fertilizers. Therefore, transitioning from intensive monocultures to diversified rubber agroforestry practices should actively be promoted by agricultural policies and extension services to ensure long-term ecological sustainability and climate resilience for farming communities.

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