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Exploring the Diverse Benefits of Pine Needle Litter for Environmental Sustainability and Economic Development: A Systematic Literature Review

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Abstract | Pine leaf litter is a valuable natural resource but has yet to be fully utilized. This systematic review highlights its potential use across various sectors through cross-disciplinary research to integrate pine leaf litter into sustainable practices. This research method uses PRISMA2020 guidelines for a systematic literature review in March 2024 by determining eligibility criteria, identifying sources, selecting studies, collecting data, and extracting relevant information. The results showed various benefits and impacts on the environment, agriculture, and industry. Research trends are still around its use in agriculture and the environment, while its use in industry is still rarely explored. In terms of the environment, pine leaf litter provides benefits in erosion control of up to 60 % and soil moisture retention, soil nutrient cycling, and habitat provision. Pine leaf litter is useful for natural mulching and weed control by up to 62 %. In the industrial sector, the benefits of pine leaf litter include bioenergy raw materials and the production of bioplastic materials. Information on environmental economics and the use of pine litter in agriculture and industry is still limited, making it a novelty in this study, and it can be a research agenda in the future, especially to increase the economic value of pine leaf litter and maintain environmentally sustainable economic.

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Introduction

A pine forest is an ecosystem with evergreen conifers, needle-like leaves and conical production. Pine forests cover vast territories on various continents, ranging from temperate to subtropical and tropical zones (Usoltsev *et al.*, 2017). These ecosystems provide multiple ecosystem services and are home to diverse plant and animal species widespread in various world regions (Brockerhoff *et al*., 2017). In North America, pine forests are widespread in the Southeastern part of the United States and are an important component of regional ecosystems (Tor-ngern, 2015). Meanwhile, in Europe, forests are dominated by the Scots pine (*Pinus sylvestris* L.), a species that plays a key role in forest ecosystems in Europe and Asia, as revealed by previous studies (Danielewska, *et al*., 2015; Zagirova and Mikhail, 2021). In Asia, pine forests have a fairly wide distribution, distributed in various regions, including subtropical and tropical areas. For example, the Chir Pine forest in Murree, Pakistan, is in the subtropical region (Hussain *et al*., 2024) and the pine forest in Central Vietnam is in the tropical region (Lu *et al*., 2022).

In current development, the pine forest is not only a natural forest, but pine has been planted into an artificial forest that has economic value as a provider of raw materials for the timber industry, producing rubber, pine forests are developed as tourist forests (Imanuddin *et al*., 2020). In addition to creating these products, pine forests produce by-products, namely pine needle fragments. The production of this litter can reach 12.88 t ha^{-1} (Putra *et al*.,2023). Meanwhile, producing this amount of litter is considered organic waste that disturbs the cleanliness of certain areas and needs cleaning (Selbig, 2016).

In fact, recent studies have revealed that pine leaf litter has very diverse benefits and has significant impacts in several aspects, including the environment and agriculture and has an important role in maintaining the function of forest ecosystems (Fu *et al*., 2021; Haynes *et al*., 2018; Kimura *et al*., 2015; Liu *et al*., 2021; Rodrigues-Corrêa *et al*., 2012; Sharma *et al*., 2021; Stavi, 2020). On the other hand, pine leaf litter can contribute to the development of potential industrial applications (Akhtar *et al*.,2016). Processing pine leaf litter can produce various products, such as developing environmentally friendly plastics (Ncube *et al*., 2020; Silva *et al*., 2018; Stamm *et al*., 2019). Using pine leaf litter as raw material in industry can reduce the use of non-recycled raw materials, reduce waste and improve resource efficiency.

Pine leaf litter's diverse applications and environmental benefits underscore its importance as a research subject. Exploring its potential uses in ecological sustainability, agriculture and industry can unlock innovative solutions that support sustainable practices and economic development. Therefore, pine leaf litter is not just a waste product but a valuable resource that warrants detailed scientific exploration to harness its full potential for improving our environment and society.

Learning the benefits of pine leaf litter is important to support the development of environmentally friendly and sustainable agricultural practices needed in the future. This litter is a source of organic matter in the pine forest ecosystem and surrounding agricultural land. It is also related to biodiversity because it is a habitat for various soil organisms (Prescott and Vesterdal, 2021). However, some limitations need to be considered when using pine leaf litter. Namely, the decomposition is relatively long and depends on the type of pine and the climate (Canessa *et al*., 2020). In addition, the benefits are limited in other areas that are not overgrown with pine, even though pine leaves are suitable for agriculture in the area around the pine forest.

Various studies on pine needle litter that have been carried out have not been mapped using systematic literature reviews to identify research trends and gaps, exploring the benefit and economic potential of pine needle litter. Therefore, this systematic literature review explores and analyzes some of the benefits of pine leaf litter identified in published scientific papers. The potential of pine leaf litter is explored in the context of environmental sustainability and local economic development. By summarizing and analyzing previous research, we can discover the research gap. Any area that requires further research can direct new research to less-explored topics. Similarly, the review can map knowledge development about pine leaf litter over time and identify research trends.

The method that can be used to analyze the purpose of this review literature is PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Page *et al*., 2021). According to prior knowledge, no research has been mapping the benefits and economic development of pine leaf litter using PRISMA, which was reported recently. Based on this, this systematic review aims to review and evaluate the benefits of pine leaf litter, using PRISMA-2020 guidelines to ensure a rigorous and reproducible methodology (Haddaway *et al*., 2022). In compliance with PRISMA-2020 guidelines, this review will provide a comprehensive and detailed overview of the benefits of pine leaf litter, systematically summarizing the available evidence.

Materials and Methods

The systematic literature review is scheduled for March 2024 and will adhere to the preferred reporting items for systematic reviews and meta-analyses using PRISMA-2020 guidelines. The PRISMA-2020 serves as the methodological framework for this study, assisting authors in systematically conducting a comprehensive literature review (Ismail *et al*., 2021). According to Liberati *et al*. (2009), this method involves several key stages:

1. Establishing eligibility criteria.
2. Identifying information sources.
3. Selecting studies.
4. Conducting the data collection process.
5. Selection of data items.
6. Eligibility criteria

Inclusion Criteria (IC) for the Systematic Literature Review are established as follows:

- IC1: The review will consider original, peer-reviewed literature written in English, available as Open Access and published from 2010 to 2023.
- IC2: This study focuses on investigating and assessing the benefits associated with pine leaf litter.
- IC3: A quantitative methodological approach will be employed in this study, involving numerical data collection and statistical analysis to objectively evaluate the advantages of pine leaf litter.

For Inclusion Criterion 1 (KI1), the selection is only for research written in English, considering that English is a common language in scientific publications. The studies included are those published until 2024 to ensure that the data and information generated are current and relevant. In addition, only open sources are considered to facilitate more comprehensive access and regular information updates. Meanwhile, Inclusion Criterion 2 (KI2) focuses on recent research findings that have revealed that pine leaf litter offers diverse benefits, exerting significant impacts on several aspects, including the environment, agriculture and potential applications in industry (Rodrigues-Corrêa, 2012). Inclusion Criterion 3 (KI3) sets the focus of research on journal articles that apply quantitative methods in their research. Thus, journal articles using qualitative research methods will be excluded from this study, therefore ensuring an analysis based on numerical and statistical data that can be objectively measured.

Sources of information

Information searches are conducted in online databases with extensive academic studies, namely PubMed, Scopus and Google Scholar. Articles that were not fully accessible were also excluded from the study.

Study options

The study selection process is carried out in three stages as follows:

1. The initial search was conducted using specific keywords that fit the purpose of the study, focusing on the benefits offered by pine leaf litter or other related terms. Search keys include the following terms: "pine leaf litter," and "pine needle litter."
2. The articles are explored and selected based on the relevance of their titles, abstracts and keywords to predefined eligibility criteria.
3. Advanced exploration involves selecting all articles that meet the notability criteria and thoroughly reviewing each article identified at the previous stage to ensure that every relevant article is noticed.

Data collection process

Data is collected manually by extracting data based on content analysis, including article type, journal name, year of publication, topic, title, research methodology, respondents/research data and country of research location.

Data items

The data items taken from each article are summarized into the year of publication, researchers, countries and samples, research objectives and research results on the benefits offered by pine leaf litter. Figure 1 presents the stages of the systematic literature review in full.

Results and Discussion

Search results in the PubMed, Scopus and Google Scholar databases use the keywords "pine leaf litter," and "pine needle litter." Produced 245 published articles written in English. The articles were then explored and selected based on IC2 and IC3 by considering titles, abstracts and keywords, resulting in 93 articles. In the next step, the rest of the article is read in its entirety and some articles cannot be accessed, so they were excluded from this research. Finally, 21 articles are left for further analysis based on this process.

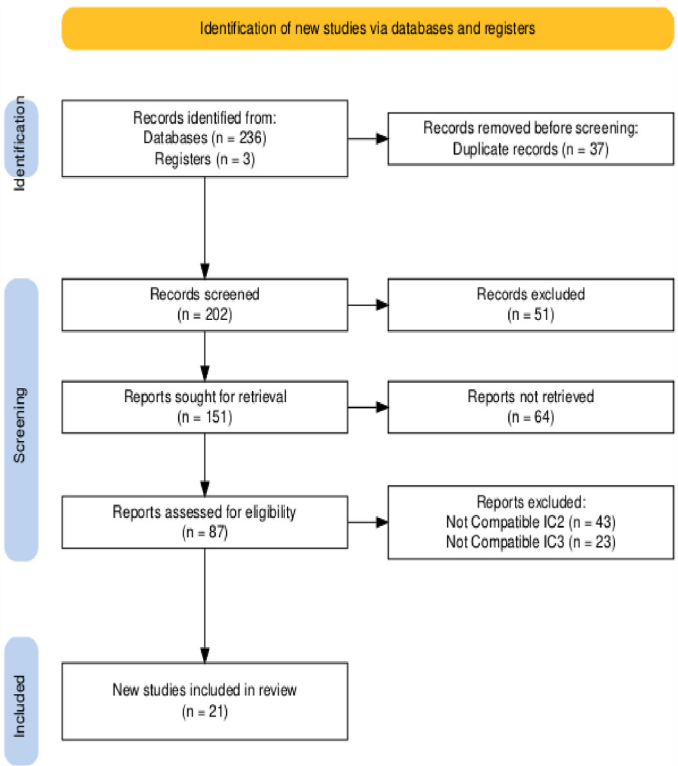

Figure 1: *Prisma flowchart.*

Analysis of published journals shows that research on the benefits offered by pine leaf litter has been relatively rare throughout the past few decades. Data shows that few journals cover this topic in any given year, with consistently low numbers from 2010 to 2023. For example, only one journal was available in those years, except in specific years when there were two relevant journals. The high sustainability of studies related to the benefits offered by pine leaf litter in recent years, as illustrated in Figure 2, shows that exploring its potential and impact is still important. This indicates that this topic is still relevant and essential in the context of scientific research, especially related to environmental and sustainability issues. Therefore, this analysis provides a strong impetus to continue further research in this regard to improve our understanding of the role and benefits of pine leaf litter in ecosystems and environmental sustainability. Furthermore, it is summarized from 21 selected articles, as shown in Table 1.

The review highlights the diverse benefits of pine leaf litter in various fields, including environment, agriculture and industry. In terms of the environment, pine leaf litter provides benefits in erosion control and soil moisture retention, soil nutrient cycling and habitat provision. Pine leaf litter is useful for natural mulching and weed control in agriculture. In the industrial sector, the benefits of pine leaf litter include bioenergy raw materials and the production of bioplastic materials.

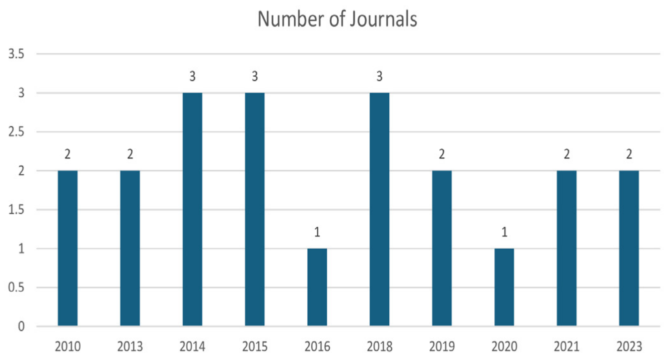

Figure 2: *Journal distribution from 2010 to 2023.*

Regarding the environment, pine leaf litter significantly influences erosion control and soil moisture retention. Research by Wang *et al*. (2013) indicates that the litter layer acts as a moisture buffer that facilitates methane absorption from the atmosphere into the soil, highlighting the importance of pine leaf litter in maintaining overall soil moisture. Li *et al*. (2014) also found that pine leaf litter effectively reduces surface runoff and soil erosion, increases water infiltration and decreases sediment loss during rainfall simulations. Moreover, Seitz *et al*. (2015) demonstrated that the interaction between litter cover and soil fauna populations significantly impacts soil protection against erosion.

Pine leaf litter also contributes crucially to soil nutrient cycling. Chae *et al*. (2019) showed that the decomposition rate of litter is influenced by its physical and chemical properties, such as specific leaf area (SLA) and surface area to volume ratio (SA/V), which directly affect soil nutrient cycling. Kriiska *et al*. (2021) emphasized the importance of pine leaf litter in the nitrogen, phosphorus and potassium cycles, with nutrient release rates positively correlating with the initial nutrient concentrations in the litter. Zhang *et al*. (2023) found that soil fauna accelerates the release of carbon and nitrogen from litter during decomposition, improving litter quality and influencing nutrient release across different elevations.

Table 1: *The list of benefits offered by pine leaf litter.*

Category	Benefit	Authors	Year	Result
Environment	Erosion control and soil moisture retention	Wang *et al.*	2013	The litter layer has an important role as a buffer triggered by moisture, which supports the absorption of methane in the atmosphere by the soil. This impact confirms the crucial role of pine leaf litter in maintaining overall soil moisture.
		Li *et al.*,	2014	Pine leaf litter cover *(Pinus tabulaeformis*) is effective in reducing surface runoff and soil erosion. Rain simulations showed that pine leaf litter increased water infiltration and reduced the amount of sediment lost.
		Seitz *et al.*	2015	In the context of protection against soil erosion, the interaction between pine leaf litter cover and soil fauna populations has a significant impact.
	Soil nutrient cycle	Chae *et al.*	2019	The rate of decomposition is affected by the physical and chemical properties of litter, such as specific leaf area (SLA) and surface area to volume (SA/V) ratio. Litter with higher SLA and SA/V has a faster decomposition rate, which directly affects the nutrient cycle in the soil.
		Kriiska *et al.*	2021	Pine leaf litter plays an important role in the nitrogen cycle, phosphorus and potassium in the soil, with nutrient release rates positively correlated with the initial nutrient concentration in the litter.
		Zhang *et al.*	2023	Soil fauna accelerates the release of carbon (C) and nitrogen (N) from litter during decomposition. Soil fauna plays an important role in improving litter quality, which affects nutrient release at various altitudes. This study highlights that the interaction between soil fauna and litter properties affects the soil nutrient cycle.
	Habitat preparation	Mjöfors *et al.*	2015	The decomposition of pine needle litter plays an important role in habitat formation by modulating nutrient flux and providing a food source for soil microorganisms, ultimately supporting biodiversity and healthy ecosystem structures.
		Bani *et al.*	2018	Microbial communities, especially fungi, play a crucial role in the decomposition of pine leaf litter and dead wood, potentially affecting the nitrogen content in the litter.
		Liu *et al.*	2021	The formation of pine leaf litter crust in sandy ecosystems also improves soil function through the contribution of bacterial taxa to soil nutrient cycling and enzyme activity.
Agriculture	Natural mulching	Adili *et. al*	2013	The use of pine leaf litter as mulch can significantly increase soil moisture and reduce soil erosion by up to 60%. In addition, this mulch also helps to improve soil structure and support plant growth.
		Aučina *et al.*	2014	Pine litter significantly increases the growth of Scottish pine seedlings as well as increases the diversity of mycorrhizal fungi.
		Hozayn *et al.*	2015	In potting experiments, pine litter proved effective at suppressing weed growth, with weed biomass (walnut grass) decreasing by 62%. Meanwhile, under field conditions, the decrease in weed biomass is also significant, reaching up to 27%.
	Weeds handling	Berg *et al.*	2010	The effect of weed control using pine leaf litter mulch is effective in reducing relative weed cover, which helps in better tree growth and increased biomass.
		Kimura *et. al*	2014	Pine leaf litter was identified as containing allelopathy substances that can inhibit the growth of certain plants.
		Saha *et. al*	2018	Pine leaf litter inhibits weed growth through light exclusion, acts as a physical barrier, reduces the moisture available to weed seeds and releases allelochemicals that can inhibit the germination or growth of some weed species.
Industry	Bioenergy raw materials	Naik *et al.*	2010	The potential of pine leaf litter for bioenergy production is very high because it has a high cellulose and hemicellulose content.
		Akhtar *et al.*	2016	Pine leaf litter, as a type of biomass, has been identified as a potential feedstock for biofuel production because it has a high cellulose content and low ash content.
		Wawro *et al*	2023	This biomass has a high potential to produce bioethanol with the highest yield of 1.08 m^3 per hectare.
	Production of bioplastic materials	Silva *et al.*	2018	These components of pine leaf litter can be utilized in the development of biopolymers, such as polylactic acid and starch-based biopolymers, which have been proposed as sustainable alternatives to conventional plastics.
		Stamm *et al.*	2019	Chemo-enzymes have been explored to convert forest waste products, including pine leaf litter, into multi-functional polymers, further highlighting the potential for sustainable plastic development.
		Ncube *et al.*	2020	The abundantly available pine leaf litter provides promising opportunities for the development of environmentally friendly plastics.

In habitat preparation, Mjöfors *et al*. (2015) reported that the decomposition of pine needle litter is vital for habitat formation, modulating nutrient fluxes and providing food sources for soil microorganisms, which support biodiversity and healthy ecosystem structures. Bani *et al*. (2018) highlighted the role of microbial communities, especially fungi, in decomposing pine leaf litter and dead wood, potentially affecting the nitrogen content in the litter. Liu *et al*. (2021) demonstrated that forming pine leaf litter crusts in sandy ecosystems enhances soil function through bacterial contributions to nutrient cycling and enzyme activity.

In agriculture, using pine leaf litter as natural mulch offers significant benefits. Research by Adili *et al*. (2013) indicates that pine leaf litter mulch can significantly enhance soil moisture and reduce erosion by up to 60 %. Additionally, Aučina *et al*. (2014) found that pine leaf litter improves Scots pine seedlings' growth and increases mycorrhizal fungi's diversity. Hozayn *et al*. (2015) demonstrated that in pot experiments, pine leaf litter effectively suppresses weed growth by reducing weed biomass by up to 62 %.

For weed management, pine leaf litter is also highly effective. Berg *et al*. (2010) reported that pine leaf litter mulch significantly reduces weed cover, thereby supporting better tree growth and increased biomass. Kimura *et al*. (2015) identified allelopathic substances in pine leaf litter that inhibit the growth of certain plant species. Furthermore, Saha *et al*. (2018) showed that pine leaf litter suppresses weed growth by excluding light, acting as a physical barrier, reducing available moisture for weed seeds and releasing allelochemicals that can inhibit the germination or growth of various weed species.

In the industrial sector, pine leaf litter holds significant potential as a bioenergy feedstock. Naik *et al*. (2010) demonstrated that pine leaf litter contains high levels of cellulose and hemicellulose, making it a suitable candidate for bioenergy production. Akhtar *et al*. (2016) further emphasized that pine leaf litter is an excellent raw material for biofuel production due to its high cellulose content and low ash content. Moreover, Wawro *et al*. (2023) highlighted that pine needle biomass has substantial potential for bioethanol production, achieving the highest yield of 1.08 m^3 ha^{-1}. These findings underscore pine leaf litter's viability as a renewable and efficient source of bioenergy.

Furthermore, chemical components in pine leaf litter, such as terpenes, offer potential for the development of environmentally friendly plastics. The development of such plastics is urgently needed in today's world, given the adverse effects of conventional plastics on the environment. These components can be utilized in the development of biopolymers, such as polylactic acid and starch-based biopolymers, which have been proposed as sustainable alternatives to traditional plastics (Silva *et al*., 2018). Additionally, chemo-enzymatic pathways have been explored to convert forest waste products, including pine leaf litter, into multi-functional polymers, further emphasizing the potential for sustainable plastic development (Stamm *et al*., 2019). The abundant availability of pine leaf litter provides promising opportunities for the development of environmentally friendly plastics (Ncube *et al*., 2020). These advancements underscore the viability of using pine leaf litter as a renewable resource in the production of sustainable materials.

Thus, the use of pine litter in the context of agriculture raises significant potential to improve economic aspects. Pine litter can be a ground cover in gardens or farmland, maintaining soil moisture, reducing weed growth and preventing erosion. This positive impact leads to reduced costs for irrigation and weed control, as well as increased crop yields. In addition, pine litter can be processed into organic fertilizer through compost or natural decomposition, improving soil fertility and plant health and producing better harvests. Using pine litter as an organic fertilizer also helps reduce dependence on expensive chemical fertilizers and reduce negative impacts on the environment. Furthermore, pine litter can be used as raw material for producing bioenergy, such as biomass or biochar, producing electrical energy, heat, or alternative fuels, such as bioethanol or biodiesel. In this way, farmers can experience diversification of income sources and improve energy sustainability. On the other hand, pine litter is also useful as a water barrier in agricultural land, especially for plants that require high humidity and serves as a natural weed control. Overall, the use of pine litter in agriculture has the potential to reduce land management costs and increase crop productivity. Further studies related to this matter are needed to determine the economic benefits of using pine leaf litter for sustainable agricultural practices.

Research on spruce leaves to produce environmentally friendly products such as bioplastics is still rare. Therefore, this area is still open as an object of study to increase the economic value of pine leaf litter.

Conclusions and Recommendations

From an environmental aspect, research shows that pine leaf litter can improve soil health, prevent erosion and retain moisture, which is essential for biodiversity and ecosystem sustainability. On the other hand, from an agricultural aspect, pine leaf litter is useful as a natural mulch that improves soil and plant health, controls weeds and supports mycorrhizal diversity. The allelopathy properties of pine leaf litter can inhibit the growth of nuisance plants and provide natural pest control, offering an environmentally friendly and sustainable method of weed control. Meanwhile, from an industrial aspect, the potential of pine leaf litter in industry is seen in bioenergy production and the development of bioplastic materials. Its high cellulose and low ash content make it ideal as a biofuel feedstock. In addition, the chemical components of litter, such as terpenes, provide opportunities for the development of environmentally friendly plastics, which is an important step towards reducing plastic waste and developing a sustainable economy.

The results of this research are expected to form the basis for the development of policies and strategies that support the sustainable use of pine litter in the industry and advance sustainable economic growth.

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Novelty Statement

This study introduces a novel approach to agriculture, providing new insights into the benefits of pine needle litter. Unlike previous research, PRISMA was used for a systematic literature review on the environmental economics and utilization of pine needle litter in agriculture and industry, which is still limited, making this a new contribution to this research.

Author's Contribution

Ida Ekawati: designed the study, collected, analyzed and interpreted the data and wrote/revised the manuscript.
Rizal Andi Syabana and Patmawati Patmawati: Conducted the experiments.
Isdiantoni Isdiantoni, Endry Nugroho Prasetyo, Anwar Saeed Khan and Hasfiah Hasfiah: Manuscript review.
Maharani Pratiwi Kountjoro: Data visualization.
All authors have read and approved the final manuscript.

Conflict of interest
The authors have declared no conflict of interest.

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