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RESEARCH ARTICLE

Nutrient Leaching in Oil Palm Plantation: A Review on Special Reference to Fertilization Application

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ABSTRACT

This paper provides overview of the leaching challenges frequently encountered in Malaysian oil palm plantations. The oil palm (Elaeis guineensis) is a vital cash crop extensively grown in tropical regions like Malaysia, a major global palm oil producer. Given Malaysia's highly weathered and less fertile soil, efficient fertilization is essential to ensure optimal oil palm growth and yield which requires a substantial supply of soluble Nitrogen and Potassium for crop uptake. Malaysia is a tropical country and typically experiences annual rainfall exceeding 2,500mm, leading to inevitable leaching issues that impact the environment. In this review, five key aspects related to leaching problems were identified. Firstly, groundwater pollution is a concern. Runoff and deep percolation beyond the root zone can carry significant amounts of soluble plant nutrients, posing health risks when entering local community water sources due to high nitrate content. Secondly, nutrient leaching from oil palm plantations can harm freshwater systems by contributing to Nitrate Nitrogen (NO3—N) loads that can trigger surface water eutrophication, leading to algal blooms and disruptions to aquatic ecosystems. Next, intensive management of oil palm plantations can result in nutrient leaching that negatively impacts soil quality and fertility. In turn, it can reduce soil organic matter content and natural biodiversity. Excessive leaching may also hinder efficient nutrient absorption by crops, potentially causing nutrient deficiencies, manifesting as visual symptoms like necrosis and stunted growth. Lastly, if nutrients are not retained in the soil, the land can become toxic and unsuitable for future use unless a sustainable replacement strategy is employed.

INTRODUCTION

The oil palm (*Elaeis guineensis*) industry in Malaysia plays a pivotal role in Malaysia's economy, contributing significantly to its Gross Domestic Product (GDP) and employment. In 2023, Malaysia ranked as the world's second-largest producer of oil palm, accounting for 24% of the total global production, which amounted to 19 million metric tonnes (USDA, 2023). Fertilizer refers to any substance, whether organic or inorganic, derived from natural or synthetic sources, that is applied to soil to supply essential nutrients such as Nitrogen (N), Phosphorus (P), and Potassium (K) needed to support and boost plant vegetative growth. (Sabry and Kazafy, 2015). Fertilizer plays a vital role in food production, making its efficient use essential for reducing food production costs and conserving natural resources. In the context of commodity crops like oil palm plantations, fertilization significantly impacts crop productivity, accounting for 60% of the total operational cost. This expense continues to rise due to increasing prices of fertilizers, driven by higher transportation costs, labour, and especially imported raw materials. In Malaysia, the demand for fertilizer per unit area is currently on the rise, corresponding with the cultivation cycle in certain regions that have reached the third generation of planting.

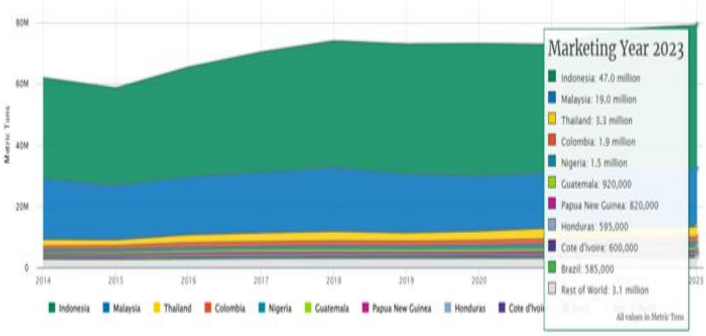

Figure 1. Comparison of palm oil production trends in Malaysia with other producer countries in 2023 (USDA, 2023)

Efficient use of fertilizer is crucial for optimizing the operational budget spent, and this efficiency is directly linked to how effectively plants absorb nutrients from the soil through their roots. The reported uptake efficiency for plant nutrients such as Nitrogen, Phosphorus, and Potassium correlates with the distance these nutrients can diffuse to reach the plant roots. However, as the cultivation cycle continues over the years, the structure of agricultural soil changes, leading to a gradual depletion of soil chemical, physical and biological properties (Jiang et al., 2024). This depletion has become a growing concern in the agricultural sector, necessitating improved fertilization strategies to sustain soil health and productivity. To maximize output and yield potential, it is crucial to consider the various factors affecting the efficiency of fertilizer application. These factors include the type of fertilizer used, soil composition, weather conditions, timing and method of application, and the specific nutrient requirements of the crops. By carefully managing these variables, farmers can optimize nutrient absorption, reduce costs and waste, and enhance overall agricultural productivity (Pawase et al., 2023). Leading plantation companies in Malaysia typically employ agronomy teams with extensive agronomic knowledge, capable of calculating and adjusting fertilizer dosages based on the age of the palms, land conditions, and topography. Additionally, the timing and frequency of fertilization are important and are primarily influenced by factors such as rainfall, soil physical properties, the availability of nutrients for plant absorption, and the type of fertilizer used (Haby et al., n.d).

When planning a fertilization program and strategy, the risk of nutrient losses shall also be considered as the possible potential factors are varies. Nutrient losses can occur through various mechanisms, such as leaching, runoff, volatilization, and erosion, which can significantly reduce the efficiency of fertilizer application. These losses not only diminish the availability of essential nutrients for plant growth but also pose environmental risks, such as groundwater contamination and eutrophication of water bodies (Rashmi et al., 2017). Moreover, due to these losses, the nutrients applied may not be available to the plants when needed, leading to decreased yields (Niemiec and Komorowska, 2018). Therefore, it is crucial to implement practices that minimize nutrient losses, such as precise fertilizer application, soil conservation techniques, and the use of slow-release fertilizers. These practices help to maintain soil fertility, promote sustainable agricultural methods, particularly in line with ESG compliance, and mitigate environmental and local ecosystem impacts. Additionally, enriching fertilizer with organic matter and effective microbes is an effective strategy to reduce chemical dependency in plantation operations.

Objective

The objective of this study is to review and synthesize existing papers and research on nutrient leaching which currently is a growing concern in the agricultural sector, particularly in oil palm plantations, with a specific focus on fertilization practices. This paper will also examine the main factors that can contribute to the risk of nutrient leaching in oil palm plantations such as the rainfall pattern, soil properties, fertilizer types, and methods. Additionally, this study will also investigate the environmental consequences of nutrient leaching such as groundwater contamination, local ecosystem disturbance, and higher greenhouse gas emissions. Furthermore, it recommends best practices for fertilizer application that can minimize nutrient leaching and align with sustainable agriculture practices. Lastly, to explore the potential benefits of integrating chemical fertilizer with organic matter and effective microbes into fertilization components to reduce chemical dependency.

METHODOLOGY

On 15th May 2024, a search using the keywords 'Nutrient Leaching Fertilizer' identified 47 highly relevant papers in the Scopus database. Bibliometric analyses are an established method for evaluating research literature, particularly in scientific fields that benefit from computational data treatment and are experiencing increased scholarly output (Ellegaard & Wallin, 2018). VOSviewer is a software tool that generates clear graphical representations of bibliometric maps, especially for extensive datasets (Van Eck and Waltman, 2010). To highlight the research trends on the topic of 'Nutrient Leaching Fertilizer' from 1975 to 2024, we performed a bibliometric analysis using VOSviewer (VOS stands for Visualization of Similarities – see www.vosviewer.com) on the 47 papers from the Scopus database.

Scopus contains a vast collection of significant research papers and provides integrated analysis tools that facilitate the creation of informative visual representations (Guz and Rushchitsky, 2009). In this study, VOSviewer was utilized to conduct a detailed analysis of each keyword, calculating the links, total link strengths, and co-occurrences with other keywords. This allowed for a comprehensive mapping of the research landscape, highlighting key trends and relationships within the data. By leveraging these tools, researchers can gain deeper insights into the interconnected nature of various research topics and their overall impact.

RESULTS

From the Scopus search with 47 papers, the category of study fields are: Agricultural and Biological Sciences (35); Environmental Science (15); Biochemistry, Genetics and Molecular Biology (6); Social Sciences (3); Medicine (2); Nursing (1); Multidisciplinary (1); Energy (1); and Earth and Planetary Sciences (1). By countries, they are: United States (14); China (6); Germany (4); Australia (4); Sweden (3) Brazil (3); Spain (2); South Korea (2); Pakistan (2); New Zealand (2); Malaysia (2); Lithuania (2); Canada (2); South Africa (1); Russian Federation (1); Norway (1); Netherlands (1); Kenya (1); Italy (1); Ireland (1); Honduras (1); Ghana (1); Czech Republic (1); and Bangladesh (1).

VOSviewer is a freely accessible computer program designed for creating and visualizing bibliometric maps. It is particularly effective for presenting large bibliometric maps in an easily interpretable manner. Employing VOSviewer provides a holistic overview of the past research based on keywords' co-occurrences with 'Nutrient Leaching Fertilizer' (Figure 1). The analysis reveals a discernible prominence reflecting four significant clusters based on 85 items, that can be identified based on visualization in Figure 3 (top), such as a) soil chemistry, b) nutrient uptake and c) nitrate leaching. Many researchers [2019-2023] have recently focused on studies such as a) leaching loss, b) surface area and c) agriculture runoff (Figure 3; bottom). The analysis shows narrowed-down 60 items from a total of 23 keywords, with 4 major clusters are formed (Figure 2; Table 1; below).

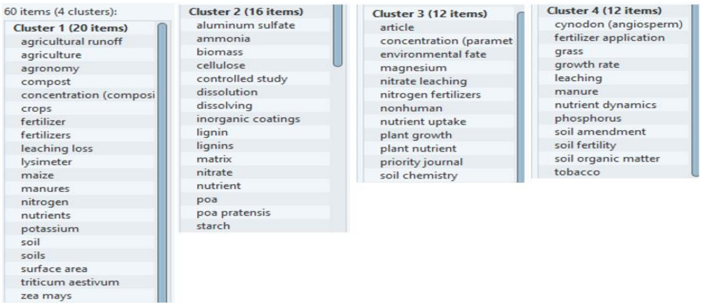

Figure 2. The Scopus analysis of past research, based on the co-occurrences of keywords related to 'Nutrient Leaching Fertilizer', identified 60 items from a total of 23 keywords, resulting in the formation of four major clusters.

Table 1. Studies conducted on the topic of 'Nutrient Leaching Fertilizer', from 1975 to 2024 based on the Scopus database.

No.	Authors	Title	Year	Source Title	Volume	Issue	Reference No.
1	Kristina Lingyte, Laima Cesoniene and Daiva Sileikiene	Leaching of nutrients after use of organic fertilizers (horn shavings)	2013	Journal of Food, Agriculture and Environment	11	3-4	48
2	Paul Hepperly, Don Lotter, Christine Ziegler Ulsh, Rita Seidel and Carolyn Reider	Compost, manure and synthetic fertilizer influences crop yields, soil properties, nitrate leaching and crop nutrient content	2013	Compost Science and Utilization	17	2	34
3	Bridget Tshikalange, Zaid A Bello and Olusola O Ololade	Comparative nutrient leaching capability of cattle dung biogas digestate and inorganic fertilizer under spinach cropping condition	2020	Environmetal Science and Pollution Research International	27	3	74
4	Navjot Kaur, Ian Pillips and Martin V Fey	Amelioration of bauxite residue sand by intermittent additions of nitrogen fertiliser and leaching fractions: The effect on growth of kikuyu grass and fate of applied nutrients	2016	The Science of the Total Environment	550	-	41

5	K.Y. Chung, J.B Sartain and E.W Hopwood	Leaching characteristics and nutrient supplying potentials of selected P and K fertilizer sources	1999	Proceedings – Soil and Crop Science Society of Florida	58	-	15
6	Richar D.J. Haynes	Leaching losses of nutrients and yield and nutrient uptake by container-grown begonia as affected by lime and fertiliser applications to a peat medium	1982	Journal of the Science of Food and Agriculture	33	5	32
7	D.O. Huett and S.C. Morris	Fertiliser use efficiency by containerised nursery plants. 3. Effect of leaching and damaged fertiliser prills on plant growth, nutrient uptake and nutrient loss	1999	Australian Journal of Agricultural Research	50	2	39
8	B. Ulen	Leaching and balances of phosphorus and other nutrients in lysimeters after application of organic manures o fertilizers	1999	Soil Use and Management	15	1	76
9	Petronella G. Ah Tung, Mohd Kamil Yusoff, Nik Muhamad Majid, Goh Kah Joo and Gan Huang Huang	Effect of N and K fertilizers on nutrient leaching and groundwater quality under mature oil palm in Sabah during the monsoon period	2009	American Journal of Applied Sciences	6	10	75
10	Crystal Vance, J. Beasley, L. Gaston, J. Macal and K Sanders	Incorporating poultry litter ash a a pre-plant fertilizer to reduce nutrient leaching during bermudagrass establishment	2019	Communications in Soil Science and Plant Analysis	50	17	79

11	D.O. Huett	Fertiliser use efficiency by containerised nursery plants 2. Nutrient Leaching	1997	Australian Journal of Agricultural Research	48	2	38
12	Raphael Adu-Gyamfi, Sampson Agyin-Birikorang, Ignatius Tindjina, Yaw Manu and Upendra Singh	Minimizing nutrient leaching from maize production system in northern Ghana with one-time application of multi-nutrient fertilizer briquette	2019	Science of the Total Environment	694	-	2
13	M.E. Engelsjord and B.R. Singh	Effects of slow-release fertilizers on growth and on uptake and leaching of nutrients in Kentucky bluegras turfs established on sand-based root zones	1997	Canadian Journal of Plan Science	77	3	20
14	M.L. Carey, E.P. Farrell and D.M. McAleese	Mobilisation of nutrients in a Sitka spruce (*Picea sitchensis*) (Bong.) Carr.) forest floor I Interaction of leaching with lime and fertilizers under laboratory conditions	1980	Forest Ecology and Management	3	-	14
15	Henrique Bley, Clesio Gianello, Lenio da Silva Santos and Lisiane Priscila Roldao Selau	Nutrient release, plant nutrition, and potassium leaching from polymer-coated fertilizer	2017	Revista Brasileira de Ciencia do Solo	41	-	9
16	Kaarel Vahtras and Lambert Wiklander	Leaching of Plant Nutrients in Soils: III. Loss of Nitrogen as Influenced by the Form of Fertilizer and Residual Effects of N Fertilizers	1977	Acta Agriculturae Scandinavica	27	3	77
17	Fatima Zahra Benlamlih, Mohammed S. Lamhamedi, Steeve Pepin, Lahcen Benomar and Younes Messaddeq	Article evaluation of a new generation of coated fertilizers to reduce the leaching of mineral nutrients and greenhouse gas (N2o) emissions	2021	Agronomy	11	6	8

18	Sherwin Chan Kit Lee, Abu Bakar Rosenani, Ch Fauziah Ishak, Azni Idris Khairuddin Abdul Rahin and Andreas Meyer-Aurich	15N-labelled fertiliser recovery by maize (Zea may L.) and leaching of nutrients as influenced by oil palm empty fruit bunch biochar in a mini-lysimeter under controlled tropical environment	2017	Archives of Agronomy and Soil Science	63	12	44
19	B.O. Mochoge and F. Beese	Leaching of plant nutrients from an acid forest soil after nitrogen fertilizer application	1986	Plant and Soil	91	1	56
20	J.M. Choi, J.W. Ahn and J.H. Ku	Growth and nutrient contents of hot pepper plug seedlings as influenced by pre-planting fertilizer levels and leaching fractions	2007	Acta Horticulturae	747	-	13
21	Mark V. Yelanich and John A. Biernbaum	Root-medium nutrient concentration and growth of poinsettia at three fertilizer concentrations anc four leaching fractions	1993	Journal of the American Society for Horticultural Science	118	6	88
22	Lambert Wiklander and Kaarel Vahtras	Leaching of Plant Nutrients in Soils: II. Loss of Nitrogen as Influenced by the Form of Fertilizer	1975	Acta Agriculturae Scandinavica	25	1	85
23	Alba Llovet, Andrea Vidal-Dura, Josep Maria Alcaniz, Angela Ribas and Xavier Domene	Biochar addition tc organo-mineral fertilisers delays nutrient leaching and enhances barley nutrient content	2023	Archives of Agronomy and Soil Science	69	13	51
24	Yunlong Li, Jianzhong Cheng, Xinqing Lee, Yi Chen, Weichang Gao, Wenjie Pan and Yuan Tang	Effects of biochar-based fertilizers or nutrient leaching ii a tobacco-planting soil	2019	Acta Geochimica	38	1	47
25	R. Meissner, H. Rupp, J. Seeger and P. Schonert	Influence of mineral fertilizers and different soil types on nutrient leaching: Results o	1995	Land Degradation & Development	6	3	53

		lysimeter studies in East Germany					
26	Xiaotong Liu, Muhammad Amjad Bashir, Yucing Geng, Qurat-Ul-Ain Raza, A. Rehim, Muhammad Aon, Jia-Chuan Luo, Ying Zhao, Xuejun Zhang and Hongbin Liu	Assessment of Nutrient Leaching Losses and Crop Uptake with Organic Fertilization, Water Saving Practices and Reduced Inorganic Fertilizer	2023	Phyton-International Journal of Experimental Botany	92	5	50
27	Kirsten N. Grant, Merrin L. Macrae, Fereidoun Rezanezhad and W. Vito Lam	Nutrient leaching in soil affected by fertilizer application and frozen ground	2019	Vadose Zone Journal	18	1	28
28	Meng Xiao, Guangming Liu, Shengguo Jiang, Xuewei Guan, Jinlin Chen, Rongjiang Yao and Xiuping Wang	Bio-Organic Fertilizer Combined with Different Amendments Improves Nutrient Enhancement and Salt Leaching in Saline Soil: A Soil Column Experiment	2022	Water (Switzerland)	14	24	86
29	Wei Mei-Juan, Yang Si-Cun, Wang Cheng-bao, Huo Lin and Jiang Wan-l	Effect of fertilizer recommendation based on Nutrient Expert system on yield and quality of melon and soil nitrogen leaching	2020	Journal of Plan Nutrition and Fertilizers	26	12	87
30	Ashok K. Alva	Differential leaching of nutrients from soluble vs. controlled-release fertilizers	1992	Environmental Management	16	6	5
31	Aukse Burakova and Eugenija Baksiene	Leaching losses of main nutrients by incorporating organic fertilisers into light texture soils haplic luvisol	2021	Environmental Engineering Research	26	4	12
32	James A. Entry and R.E. Sojka	Matrix-based fertilizers reduce nutrient leaching while maintaining kentucky bluegrass growth	2010	Water, Air, and Soil Pollution	207	1-4	21

33	Johannes Lehmann, Jose Pereira da Silva Jr, Christoph Steiner, Thomas Nehls. Wolfgang Zech and Bruno Glaser	Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: Fertilizer, manure and charcoal amendments	2003	Plant and Soil	249	2	45
34	Tatiana V. Abramova and Natalya P. Buchkina	Short-term effect of heavy precipitation on nutrient leaching from arable sandy loam soil amended with fertiliser and biochar	2022	Zemdirbyste	109	1	1
35	Michael D. Frost, Janet C. Cole and John M. Dole	Fertilizer source affects iron, manganese, and zinc leaching, nutrient distribution, and geranium growth	2003	Journal of Plant Nutrition	26	2	25
36	Cheng Huang, Xiuyun Sun, Lianjun Wang, Paul Storer, Kadambot H.M. Siddique and Zakaria M. Solaiman	Nutrients leaching from tillage soil amended with wheat straw biochar influenced by fertiliser type	2021	Agriculture (Switzerland)	11	11	37
37	Arif Reza, Soomin Shim, Seungsoo Kim, Naveed Ahmed, Seunggun Won and Changsix Ra	Nutrient leaching loss of pre-treated struvite and its application in Sudan grass cultivation as an eco-friendly and sustainable fertilizer source	2019	Sustainability (Switzerland)	11	15	65
38	O.C. Bataglia, J.A. Quanggio, M.M. Ferreira de Abreu and P.S. Ronchini Boaventura	Nutrient uptake and leaching on citrus nursery production in substrate with two fertilizer management programs	2005	Acta Horticulturae	697	-	7
39	S. Macolino and G. Zanin	Effectiveness of a zeolite-based fertilizer in reducing nutrient leaching in a	2014	Acta Horticulturae	1122	-	52

		recently sodded turfgrass					
40	Claire E. Krofft, Jeremy M. Pickens, Adam F. Newby, Jeff L. Sibley and Glenn B. Fain	The effect of leaching fraction-based irrigation on fertilizer longevity and leachate nutrient content in a greenhouse environment	2020	Horticulture	6	3	43
41	Kayla R. Sanders, Jeffery S. Beasley, Edward W. Bush and Stacia L. Conger	Fertilizer source and irrigation depth a¡ect nutrient leaching during coleus container production	2019	Journal of Environmental Horticulture	37	4	67
42	Chen Wang, Qi Miao, Zhibiao Wei, Yingxin Guo, Junying Li, Zhiyong Fan, Yanxia Hu, Hong Zhang, Junwei Sun and Zhenling Cui	Nutrient runoff and leaching under various fertilizer treatments and pedogeographic conditions: A case study in tobacco (Nicotiana tabacum L.) fields of the Erhai Lake basin, China	2024	European Journal of Agronomy	156	-	82
43	Tyler C. Hoskins, James S. Owen Jr. and Alex X. Niemiera	Controlled-release fertilizer placement affects the leaching pattern of nutrients from nursery containers during irrigation	2014	HortScience	49	10	36
44	James A. Entry, R.E. Sojka and Brendan J. Hicks	Matrix-based fertilizers reduce nutrient and bacterial leaching after manure application in a greenhouse column study	2010	Journal of Environmental Quality	39	1	22
45	Martin Brtnicky, Adnan Mustafa, Tereza Hammerschmiedt, Antonin Kintl, Lukas Trakal, Luke Beesley, Pavel Ryant, Carol Omara-Ojungu, Tivadar Baltazar and Jiri Holatko	Pre-activated biochar by fertilizers mitigates nutrient leaching and stimulates soil microbial activity	2023	Chemical and Biological Technologies in Agriculture	10	1	10

46	Pushpa Soti, Angie Fleurissaint, Stewart Reed and Krish Jayachandran	Effects of Control Release Fertilizers on Nutrient Leaching, Palm Growth and Production Cost	2015	Agriculture (Switzerland)	5	4	70
47	M. Tejada, C. Benitez and J.L. Gonzalez	Effects of application of two organomineral fertilizers on nutrient leaching losses and wheat crop	2005	Agronomy Journal	97	3	72

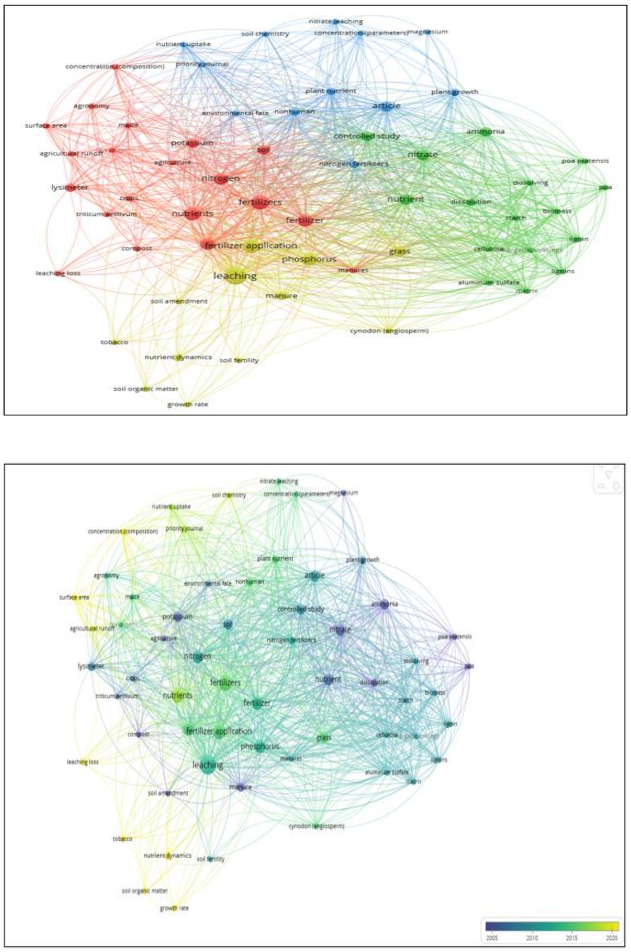

Figure 3: A bibliometric analysis of research themes on "Nutrient Leaching Fertilizer'. Top Panel: Visualization of the paper network confirming the main themes of research. Bottom Panel: Evolution of research trends between 1975 and 2024 based on the Scopus database. The colours in the top panel indicate the themes of research that the papers are discussing, while the colours in the bottom panel indicate the year of publication. 47 papers with the keyword "Nutrient Leaching Fertilizer' in the article title with initially, narrowed down to 60 items (keywords), based on the Scopus database searched on 15 May 2024.

DISCUSSION

Publication output analysis over the years

Figure 4 illustrates the annual count of publications and citations from 1975 to 2024 among the 47 highly relevant papers identified in the Scopus database, searched using the keywords "Nutrient Leaching Fertilizer." The number of publications increased significantly from 1975 to 2023, with a slight decrease observed in 2024. This upward trend is likely due to the adoption of MSPO, RSPO, and ESG compliance in recent years, leading to greater use of chemical fertilizers for higher yield production. This, in turn, has attracted more attention from scholars, researchers, and industry professionals in the field of soil nutrient research. Additionally, the easier access to online literature and the availability of digital journal archives since 1975, as opposed to traditional library subscriptions, may have also contributed to this trend.

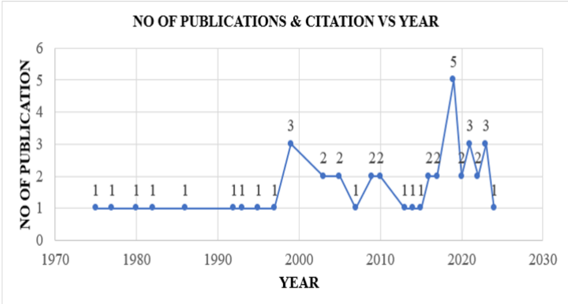

Figure 4. Annual number of publications and citations from 1975 to 2024 for the 47 highly relevant papers identified in the Scopus database, using the keywords "Nutrient Leaching Fertilizer".

The key themes and concepts between clusters

Agricultural practices, especially in oil palm production, face significant environmental and socio-economic challenges, primarily due to nutrient leaching. Based on the four Vosviewer major clusters analysis shown in Figure 2, key points and concepts within the clusters were identified with discussion is as below:

Cluster 1: Agriculture and Soil Science

Cluster 1 underscores essential elements of agriculture and soil health, encompassing 20 items focused on agricultural practices, soil sciences, and nutrient management. This cluster emphasizes the importance of sustainable agriculture and environmental conservation. Terms such as 'fertilizer,' 'nitrogen,' 'potassium,' 'soil,' and 'nutrients' highlight the critical role of nutrient efficiency in agriculture. Additionally, terms like 'leaching loss,' 'agricultural runoff,' and 'concentration' indicate that soil health is a vital factor for sustainable agriculture. Effective nutrient management is crucial to minimize leaching and enhance soil fertility. To meet ESG requirements within the industry, precise agriculture techniques should be prioritized to minimize environmental runoff and reduce the over-application of fertilizers. Furthermore, industries should offer training and programs for plantations and smallholders on sustainable farming practices and nutrient management, providing support to access resources and technologies for implementing sustainable practices.

Cluster 2: Chemical Processes and Materials

Cluster 2 comprises 16 items focused on chemical substances, processes, and materials relevant to agriculture and environmental sciences. Terms such as 'ammonia,' 'aluminum sulfate,' and 'nitrate' refer to chemicals commonly used in agricultural practices. Conversely, 'biomass,' 'cellulose,' and 'lignin' refer to organic materials derived from plants and animals, which are increasingly seen as potential sources for biofertilizers. The use of chemical-based products in plantations, such as fertilizers, herbicides, and insecticides, should be carefully monitored and managed to prevent environmental contamination. Governments are now promoting options and initiatives to reduce chemical dependency in plantations, aiming to raise awareness of the environmental impacts of chemical use and to develop strategies to mitigate negative effects. One such initiative is the use of biomass and organic materials as sustainable alternatives to synthetic chemicals.

Cluster 3: Soil Chemistry and Nutrient Dynamic

Cluster 3 comprises 12 items focused on soil chemistry and nutrient dynamics, featuring terms such as 'nitrate leaching,' 'nitrogen fertilizers,' 'nutrient uptake,' and 'plant nutrient.' These terms highlight critical processes of nutrient cycling and availability in soils, which are crucial for plant uptake to ensure optimal growth and yield production. This cluster underscores the importance of understanding how nutrients are absorbed by plants and the impact of fertilizers on these processes. Effective management of soil chemistry and nutrient dynamics is essential for improving crop yields and reducing environmental impacts, emphasizing the need for advanced and innovative practices in soil management strategies, particularly regarding fertilizer use. In the context of ESG compliance, managing soil chemistry and nutrient dynamic is significant to help in minimizing environmental footprints of agriculture activities by reducing the risk of nutrient leaching and groundwater contamination.

Cluster 4: Nutrient Dynamic and Plant Growth

Cluster 4 focuses on the dynamics of nutrient application and comprises 12 items such as 'fertilizer application', 'growth rate', 'soil amendment' and 'soil organic matter'. These terms emphasize on the critical role of effective nutrient management in promoting healthy plant growth and enhancing soil fertility. Fertilizer application practices are the centre of this cluster that highlights the importance of optimizing the types, dosage, placement, and timing of fertilizers to achieve optimal growth rates and improve yield productions. Soil amendment and organic matter are also important as they enhance soil structure, increase cation exchange capacity (CEC), increase nutrient availability, and support sustainable agricultural practices.

The significance of nutrients for oil palm growth

Sufficient supply of nutrients is important for oil palm growth as it directly influences the vegetative development, plant health and resistancy towards disease pathogens, also the crops' potential yield production. Essential nutrients, such as nitrogen (N), phosphorus (P), and potassium (K), are vital for numerous physiological processes, including photosynthesis, improve resistance to abiotic stress, and cellular function. Effective nutrient management is crucial, requiring these nutrients to be supplied at appropriate levels to support maximum crop growth. Additionally, enhancing the uptake rate of specific nutrients is important for achieving optimal yields. For instance, soil with a high calcium content can inhibit the availability of magnesium, reducing its uptake and causing nutrient imbalances within crops (Osemwota et al., 2007).

According to Liebig's Law of Minimum (1855), if one nutrient is in insufficient supply, it will trigger a chain reaction that ultimately affects the availability of other nutrients for uptake. There are around 17 essential elements known to support plant vegetative growth and yield production, which can be divided into two groups: macronutrients and micronutrients as shown in **Table 2**. These nutrients must be present in sufficient amounts and appropriate ratios for optimal crop growth. Requirements vary significantly among different plants and even between species, making plant nutrition a vast and complex subject. Nutrient deficiencies can lead to deficiency symptoms, while excessive supply can cause toxicity.

Table 1. Role of macronutrients and micronutrients according to Foth (1978).

Nutrients	Role in plants
Nitrogen (N)	Components of proteins, coenzymes, and in chlorophyll, and nucleic acids
Phosphorus (P)	Transferring energy as part of ATP
Potassium (K)	Adjusting mechanisms as translocation of carbohydrate, synthesis of protein
Magnesium (Mg)	Activator of enzyme and component of chlorophyll
Boron (B)	Vital in translocation of sugar and carbohydrate metabolism
Calcium (Ca)	Plays role in membranes structure and permeability
Zinc (Zn)	Zinc regulates several metabolic actions in the system of enzymes
Iron (Fe)	Synthesis of chlorophyll and in enzymes for the transfer of electron
Sulphur (S)	Significant component of plant proteins

Fertilization practices in oil palm cultivation

Most of the oil palm plantations in Malaysia are grown on acidic soils with low fertility levels such as, peat soils, podzolic soils, and acid sulphate soils. The current domestic demand for fertilizer is very high, but phosphate and potassium fertilizers are still imported due to the unavailability of the necessary raw materials within the country. Consequently, fertilization in the oil palm industry incurs significant operational costs. As the prices of non-subsidized chemical fertilizers continue to rise, this financial burden is particularly challenging for the industry players especially the smallholders (Dwikita, 2019).

Given the crucial role of fertilizers in the oil palm industry, users must understand that the effectiveness of fertilizer applications is influenced by various factors beyond just the selection of fertilizers. These factors include soil type, climate conditions, the specific nutrient requirements of the oil palm at different growth stages, and the timing and method of fertilizer application also directly influence nutrient availability and the risks of leaching (Azahari and Sukarman, 2023). Additionally, the integration of sustainable practices, such as the use of organic amendments and precision agriculture techniques, can significantly enhance nutrient uptake efficiency and reduce environmental impact. Properly managing these variables is essential for optimizing growth, yield, and overall sustainability in oil palm cultivation. By comprehensively addressing these factors, growers can ensure more efficient use of fertilizers, minimize costs, and support long-term agricultural productivity.

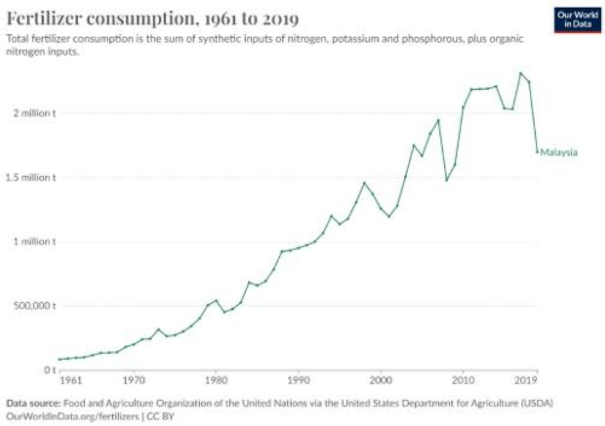

Figure 5. Malaysia's total fertilizer consumption from 1961 to 2019, based on data from Our World in Data (2024).

According to Our World in Data (2024), the fertilizer consumption in Malaysia exhibited a notable increase from 84,885 tons in 1961 to 2.31 million tons in 2017. However, this trend began to decline following the implementation of sustainability measures and enforcement efforts in Malaysia's agricultural sectors. Recent situation of oil palm sustainability in Malaysia, the use of fertilizers that comply with the Malaysian Sustainable Palm Oil (MSPO) certification and Environmental, Social, and Governance (ESG) criteria is crucial for sustainable oil palm cultivation. These standards emphasize the adoption of environmentally friendly and socially responsible agricultural practices. Fertilizers compliant with MSPO and ESG guidelines are typically those that minimize environmental impact, such as slow-release and controlled-release formulations that reduce nutrient leaching and soil degradation. They also promote the use of organic and bio-based fertilizers, which enhance soil health and biodiversity. Additionally, these standards require careful management of fertilizer application to prevent overuse, protect water quality, and reduce greenhouse gas emissions. By adhering to MSPO and ESG requirements, plantations can achieve higher sustainability, improve their ecological footprint, and ensure long-term productivity while meeting the growing global demand for responsibly produced palm oil.

Mechanisms of nutrient leaching

According to Lehmann and Schroth (2003), nutrient leaching involves the downward movement of dissolved nutrients in the soil profile due to percolating water. When these nutrients move below the rooting zone of vegetation, they are temporarily lost from the system, although they may be recycled if roots grow deeper. In regions with extensive and continuous agricultural activities, leached nutrients can accumulate in the subsoil and transported to groundwater which leads to contamination. The rate and extent of nutrient leaching are also influenced by climatic factors such as rainfall intensity duration and frequency. Nutrient leaching is significantly higher in humid regions compared to dry climates because soil water content often exceeds field capacity, occurring when water input from rainfall and irrigation surpasses the rate of evapotranspiration (Havlin et al., 1999).

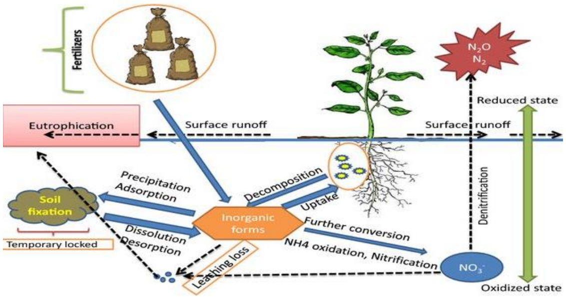

Figure 6. Pathways of nutrient losses from the soil system (Parihar et al., 2019).

In addition, one of the most influential factors in nutrient leaching is soil type. Soils with high water infiltration rates and porosity, as well as low nutrient retention capacity, such as sandy soils, soils with low clay activity, and soils with low organic matter content, are particularly prone to nutrient leaching as it facilitates rapid water movement (von Uexkull, 1986). Soil texture influences nutrient leaching by affecting soil fertility factors such as cation exchange capacity, decomposition, and nutrient cycling, as well as the soil's water-holding capacity. Fine-textured soils possess higher cation exchange capacity, decomposition rates, and soil-N cycling, resulting in better soil fertility compared to coarse-textured soils (Allen et al., 2015; Silver et al., 2000; Sotta et al., 2008). Soil texture also impacts water-holding capacity and drainage by affecting porosity, pore size distribution, and hydraulic conductivity (Hillel, 1982). Clay soils, characterized by small pores, can retain large amounts of water but have low hydraulic conductivity under high moisture conditions. In contrast, coarse-textured soils have low water-holding capacity and are dominated by large pores, which allow rapid water movement in high moisture conditions, thereby increasing the potential for leaching of dissolved solutes (Fujii et al., 2009; Lehmann and Schroth, 2003).

The oil palm is a heavy feeder that requires substantial amounts of fertilizer for both vegetative growth and yield production. Therefore, effective fertilizer management, especially in undulating and hilly terrain, is essential for minimizing nutrient leaching, maintaining soil fertility, and reducing erosion. This ensures optimal nutrient absorption and utilization by the crops. In such terrains, the risk of nutrient leaching, runoff, and soil erosion is heightened due to the slope (Goh and Teo, 2011). Excessive fertilizer use and improper placement can exacerbate these issues, leading to environmental degradation and significant reductions in yield production. Nutrient leaching peaks during specific phases of oil palm growth, particularly immediately after land-clearing, when there is a heightened risk of significant losses. During this period, the soil surfaces are exposed, making them susceptible to erosion and uncontrolled runoff before the establishment of cover crops and legumes. Furthermore, the leaching losses from fertilizer application were reduced in older palms compared to younger ones, attributed to the better rooting system of mature palms, which facilitates the absorption of applied nutrients (Omoti et al., 1983).

Impacts of nutrient leaching

Nutrient leaching from fertilizers can significantly increase nitrogen decomposition, resulting in lower pH in the leachate and slowing the decomposition of soil organic matter. This process can have wide-ranging environmental impacts (Messiga *et al*., 2020). Inadequate fertilizer management, for instance, can lead to adverse effects such as algae blooms caused by excess nitrogen entering water bodies. These blooms not only deplete oxygen levels in surface waters, posing a serious threat to aquatic life, but also impact water quality. Managing water bodies is crucial, especially in regions like Malaysia where many oil palm plantations are near settlements and various ecosystems, making these water sources essential for drinking water and other daily activities.

Moreover, nutrient leaching can introduce pathogens and nitrates into drinking water, posing significant health risks to nearby communities. Elevated nitrate levels in drinking water can trigger methemoglobinemia in humans and mammals, a condition that disrupts oxygen uptake in the circulatory system. Improper handling of fertilizers can also lead to foul odours being emitted into the air, further impacting the quality of life for residents in the vicinity. Proper fertilizer management is therefore essential not only for crop health but also for environmental and public health. Additionally, nutrient leaching resulting from fertilizer application can lead to elevated levels of nitrates, posing a risk to surrounding ecosystems. Nitrates not absorbed by the soil can freely permeate into groundwater, leading to heightened concentrations of nitrates in water sources. While nitrate itself is not inherently toxic to animals, elevated levels may induce a condition known as nitrate poisoning, particularly prevalent among ruminants and livestock. This occurs when animals ingest excessive nitrates from plant and water sources (Whittier, 2011). Therefore, proper fertilizer management practices are crucial to prevent such adverse outcomes and ensure the sustainability of agricultural practices and the protection of both environmental and public health.

The risks associated with nutrient runoff into lakes and streams are exacerbated by factors such as heavy rainfall and inadequate soil conservation practices. Runoff water originating from areas with elevated levels of soil-test nitrogen and phosphorus may contain increased concentrations of dissolved nutrients, exacerbating the risk of contaminating local water bodies (Keena, Meehan and Scherer, 2022). This scenario highlights the critical need for the implementation of effective soil and water management practices, including the use of buffer zones, cover crops, and conservation tillage, to mitigate nutrient runoff and safeguard water quality. Additionally, community-based initiatives and government regulations play a vital role in promoting sustainable agricultural practices and reducing the impact of nutrient leaching on aquatic ecosystems.

Fertilizer nutrient leaching can also have implications for the atmosphere, primarily through the release of nitrogen-based gases. Chemical fertilizers, particularly those containing ammonium or urea, can contribute to the emission of nitrous oxide (N2O), a potent greenhouse gas that significantly contributes to climate change. Moreover, excessive nitrogen application can lead to ammonia (NH3) volatilization, resulting in air pollution and posing risks to respiratory health (Burakova and Baksiene, 2020). These emissions not only affect local air quality but also contribute to broader environmental challenges, underscoring the importance of sustainable fertilizer management practices to mitigate these atmospheric impacts.

Strategies to mitigate nutrient leaching

Balancing the nitrogen required for optimal plant growth with the need to minimize nitrate (NO3) transport to ground and surface waters is a significant challenge for those seeking to enhance agricultural nutrient use efficiency (Dinnes *et al*., 2002). The reputation of oil palm has suffered due to the negative environmental impacts of its cultivation, notably deforestation, loss of biodiversity, and greenhouse gas emissions resulting from the expansion of plantations. Nutrient depletion in agriculture, especially in oil palm farming, poses significant challenges to achieving sustainable plantation practices and environmental conservation (Paterson and Lima, 2018). To promote sustainable agriculture and protect ecosystems, agricultural practices must incorporate strategies and policies aimed at minimizing nutrient losses and environmental impacts. One effective approach involves the adoption of precision farming techniques, wherein fertilizers are applied at precise rates, frequencies, and timings determined by soil nutrient levels, crop requirements, topographical considerations, and prevailing weather conditions (Tripathi et al., 2021).

The said approaches help to minimize excess nutrient application and eventually reducing the risk of leaching. Implanting conservation tillage practices, such as no-till or reduced tillage can also help to improve soil structure and reduce erosion, thereby reducing nutrient runoff and potential leaching (Liu et al., 2021). Additionally, integrating cover crops into crop rotations can help to improve soil health and fertility, enhance soil physical, chemical and biological properties, increase organic matter content, and reduce nutrient leaching by capturing and retaining nutrients in the soil. Furthermore, employing biofertilizers, controlled-release fertilizers, and nutrient management technologies, such as soil testing, foliar analysis, and nutrient budgeting, can optimize nutrient use efficiency and reduce nutrient losses through leaching. Utilizing bio-chemical fertilizers that contain agriculturally beneficial microorganisms can also contribute directly to biological nitrogen fixation, phosphate solubilization, and phytohormone production as shown in Figure 7 (Bargaz et al., 2018; Sundram et al., 2019)

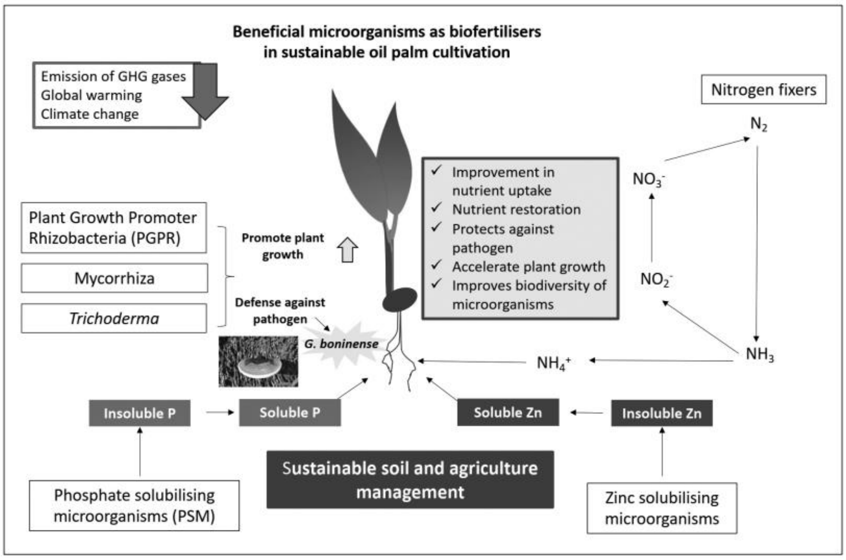

Figure 7. Potential use of agriculturally beneficial microorganisms as a biofertilizer for sustainable oil palm cultivation (Sundram et al., 2019).

The Malaysian government has implemented several policies and enforcement measures to address nutrient leaching issues and their environmental impacts. Notable initiatives include the National Green Technology Policy established in 2009, the National Renewable Energy Policy and Action Plan introduced in 2010, and the Renewable Energy Act of 2011, all aimed at reducing greenhouse gas emissions (Ahmad et al., 2018). Policymakers play a crucial role in mitigating fertilizer nutrient leaching and promoting sustainable agricultural practices. Through the development and implementation of regulations and incentives, they can encourage farmers to adopt practices that minimize nutrient losses and environmental impacts. This can include setting guidelines for fertilizer use, such as application rates and timing, and requiring soil testing and nutrient management planning. Additionally, policymakers can incentivize conservation practices like cover cropping and conservation tillage through financial support or tax incentives. Moreover, policymakers can facilitate research and extension programs aimed at improving nutrient management practices and promoting sustainable agriculture. By collaborating with stakeholders, including farmers, researchers, and environmental organizations, they can create a regulatory framework that supports environmentally responsible agriculture while ensuring the long-term viability of agricultural systems.

CONCLUSION

Supplying balanced nutrients to oil palm cultivations is crucial for producing high-quality yields in a sustainable planting environment. However, low nitrogen use efficiency remains a common global problem, often resulting from improper fertilization, surface runoff, leaching, volatilization, nitrification, and denitrification. These issues can lead to significant environmental problems, including water eutrophication, groundwater pollution, and excessive greenhouse gas emissions. Controlled-release or slow-release nitrogen fertilizers have been demonstrated to improve nitrogen use efficiency, offering both economic and eco-friendly benefits (Guo et al., 2020).

In conclusion, nutrient leaching in oil palm plantations presents a significant challenge, particularly in the context of fertilizer application. This review highlights the critical need for effective nutrient management strategies to mitigate the environmental impacts of nutrient leaching. The implementation of biofertilizers, bio-organic and bio-chemical fertilizers, controlled-release fertilizers, and advanced nutrient management technologies, such as soil testing, foliar analysis, and nutrient budgeting, has shown promise in optimizing nutrient use efficiency and reducing nutrient losses. Furthermore, the role of policymakers is paramount in addressing these issues. By developing and enforcing regulations and providing incentives for sustainable agricultural practices, policymakers can encourage the adoption of best practices that minimize nutrient leaching. This includes setting guidelines for fertilizer application, promoting conservation practices, and supporting research and extension programs.

The Malaysian government's initiatives, such as the National Green Technology Policy, the National Renewable Energy Policy and Action Plan, and the Renewable Energy Act, serve as examples of how policy interventions can contribute to reducing the environmental impacts of agricultural practices. Collaborative efforts among stakeholders, including farmers, researchers, environmental organizations, and higher education institutions, are essential for creating a sustainable framework for nutrient management in oil palm plantations. Ultimately, achieving sustainable nutrient management in oil palm plantations requires a holistic approach that integrates scientific advancements, policy support, and stakeholder collaboration. By addressing the issue of nutrient leaching through comprehensive and coordinated efforts, it is possible to ensure the long-term environmental sustainability and productivity of oil palm plantations.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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