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A Special Issue devoted to
Smart and Sustainable Agriculture

Guest Editors
Ahmed Abubakar, Md Kamal Uddin, and SM Shamsuzzaman

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Pertanika Journal of Tropical Agricultural Science
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Preface

The rapid evolution of technological innovation, coupled with the increasing necessity for sustainable resource management, has created both profound challenges and transformative opportunities for global agricultural systems. In an era marked by climate variability and growing food security demands, agriculture must extend beyond traditional production methods by integrating precision technologies, bio-innovations, and advanced crop management strategies. Fostering research and interdisciplinary collaboration is therefore essential to support agricultural practices that are resilient, sustainable, and future-ready.

It is an honour to present this Special Issue of the *Pertanika Journal of Tropical and Agricultural Science* (PJTAS), entitled "Smart Agriculture and Sustainable Crop Production: Enhancing Resilience to Environmental Stresses", under the theme "Smart and Sustainable Agriculture". This collection brings together cutting-edge research and comprehensive studies that significantly advance sustainable agricultural practices and crop production systems.

The contributions featured in this special issue address critical dimensions of modern agricultural science. Research on smart agriculture highlights the integration of digital tools, data-driven approaches, and advanced monitoring systems to optimise input efficiency, resource management, and crop yield stability. Studies on sustainable crop production explore innovative agronomic practices, soil health management, and physiological approaches to enhance crop resilience to biotic and abiotic stressors. Furthermore, articles emphasising environmental stress adaptation and technological integration underscore the importance of mitigating climate impacts and ensuring the long-term viability of the agri-food system.

Collectively, these contributions demonstrate that achieving long-term sustainability in agriculture requires a holistic approach that combines technological precision, resilient crop management, and adaptive biological solutions. Such integrated strategies are key to building agricultural systems that are both environmentally sound and robust against global environmental challenges.

We sincerely appreciate all the authors for their valuable research contributions, the peer reviewers for their rigorous and constructive evaluations, and the Editorial Team of PJTAS for their unwavering support and dedication throughout

the preparation of this publication. We hope that this Special Issue serves as a valuable resource for researchers, practitioners, and policymakers, inspiring further innovation and collaboration toward smart and sustainable agricultural systems.

Guest Editor
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Review Article

Review of the IoT-Enabled Sensor System for Nutrient Management in Crop Production: Sensor Technologies and Future Trends

Md. Asib Biswas[1,2], Md. Kamal Uddin[1]*, Susilawati Kasim[1], Mohd Firdaus Mohd Anuar[1], S.M.M. Shahriar Tonmoy[1,2], Ahmad Suhaizi Mat Su[3], Fakrulradzi Idris[4], and A K M Zakir Hossain[5]

[1]*Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia*
[2]*Fram Management Division, Bangladesh Rice Research Institute, 1701 Gazipur, Bangladesh*
[3]*Department of Agriculture Technology, Faculty of Agriculture, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia*
[4]*Centre for Telecommunication Research and Innovation, Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer, Universiti Teknikal Malaysia Melaka, Durian Tunggal, 76100 Melaka, Malaysia*
[5]*Department of Crop Botany, Faculty of Agriculture, Bangladesh Agricultural University, 2202 Mymensingh, Bangladesh*

ABSTRACT

Optimising nutrient management is critical for sustainable and cost-effective crop production. This review investigates how Internet of Things (IoT) sensor technologies help farmers monitor nitrogen (N), phosphorus (P), and potassium (K) to support precision farming. Although IoT-based nutrient sensing devices have developed rapidly, most existing reviews focus on a single sensing technology or general precision agriculture applications. Few integrate sensor technologies, calibration approaches, field validation, and future trends in real-time NPK management. This review addresses that gap by examining IoT-enabled NPK sensor systems for precision fertiliser management. Current research explores NPK sensors using electrochemical and optical technologies, alongside pH, moisture, and temperature sensors, microcontrollers, communication modules, and cloud-based platforms. When properly calibrated, IoT-based NPK systems can provide reliable real-time nutrient monitoring and improve nutrient use efficiency (NUE) through sustainable practices, potentially increasing crop yields while reducing environmental impact.

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E-mail addresses:
asibbau71@gmail.com (Md. Asib Biswas)
mkuddin@upm.edu.my (Md. Kamal Uddin)
susilawati@upm.edu.my (Susilawati Kasim)
m.firdaus@upm.edu.my (Mohd Firdaus Mohd Anuar)
smstonmoy47@gmail.com (S.M.M. Shahriar Tonmoy)
asuhaizi@upm.edu.my (Ahmad Suhaizi Mat Su)
fakrulradzi@utem.edu.my (Fakrulradzi Idris)
zakir@bau.edu.bd (A K M Zakir Hossain)
* Corresponding author

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The review evaluates calibration methods, their advantages and disadvantages, and their effects on field testing and sensor performance over time. It also considers agricultural applications across major crop types and identifies challenges involving farm operations, reliable data, rural internet access, and electronic waste. This assessment highlights the potential of IoT-integrated NPK sensing for precision fertiliser management and real-time nutrient monitoring, while emphasising the need for better calibration, reliability, and field validation. Integrating advanced sensing technologies with precision farming tools and artificial intelligence could support more efficient nutrient management and sustainable crop production.

Keywords: Internet of Things (IoT), NPK sensor, precision agriculture, sensor calibration, nutrient management, real-time nutrient monitoring

INTRODUCTION

Researchers need to develop efficient, sustainable methods for growing crops to solve the dual problem of rising population numbers and environmental limitations that block global food security. The world needs to enhance its agricultural productivity because the global population will reach 9.7 billion by 2050 (Food and Agriculture Organization [FAO], 2017). The main challenge which researchers face in this field involves handling three vital macronutrients, which include nitrogen, phosphorus, and potassium, because these elements enable plants to grow, develop, and produce their maximum yields (Sardans & Peñuelas, 2021). Fertilisation methods used in traditional farming systems lead to problems because they result in excessive nutrient application, creating unsustainable soil conditions, environmental harm, and increased operational expenses (Chojnacka & Moustakas, 2024).

Farmers who apply fertiliser s without proper timing or application methods harm soil health and create nutrient runoff problems, which decrease their farming profits (Pandian et al., 2024). To solve these problems, researchers require the urgent development of nutrient management solutions that use site-specific data to optimise input methods based on actual soil and crop conditions (Vullaganti et al., 2025). Precision fertilisation, supported by advances in sensing technologies, enables farmers to boost nutrient use efficiency, reduce environmental hazards, and achieve better financial outcomes (Getahun et al., 2024).

Smart farming, which uses IoT, remote sensing, AI and big data analytics, has brought about fundamental changes to traditional agricultural methods. IoT-enabled sensor systems provide continuous monitoring of essential parameters, including NPK levels and soil pH, temperature, and moisture (Anwar et al., 2023; Hashim et al., 2024). The system uses soil sensor networks that connect to low-power microcontrollers and wireless communication protocols, such as LoRaWAN, to provide operators with real-time data via cloud-based dashboards. Farmers can use the integrated system to obtain fertilisation

recommendations that adapt to changing field conditions (Idris et al., 2024). IoT-based fertigation systems reduce human intervention and minimise human error compared to conventional manual fertigation (Idris et al., 2024). IoT-based farming helps reduce time and energy for farmers while minimising resource waste, potentially increasing crop productivity . The potential application of IoT in smart irrigation systems will help conserve water, reduce water usage by 70%, further improve crop production, and create a huge opportunity for water resources conservation and food security (Morchid et al., 2026). Most current IoT-based nutrient management systems are still at the prototype or experimental stage. They often lack proper agricultural experimental design standards and validation through plant-based testing. The majority of existing research focuses only on nutrient monitoring, not on complete nutrient management or optimisation of fertiliser practices (Fauziah et al., 2024). The recent improvements in IoT-based fertigation technology, which is a combination of NPK sensors and microcontrollers, have demonstrated that their integration has triggered a notable increase in the efficiency of nutrient delivery, bringing about the consumption of fertiliser being reduced by as much as 30%, leading to the same or higher yield (Inayah et al., 2026).

Although there has been some progress, current research and review articles mainly cover basic sensor technologies or nutrient-monitoring applications and do not address the integration of sensor technologies, calibration techniques, Internet of Things (IoT) architecture, field validation, communication technologies, and practical fertiliser management strategies within a comprehensive system. Furthermore, many IoT-based nutrient management systems are still in the prototype/experimental stage and have not been standardised in agricultural experimental designs, widely tested in the field, or evaluated in depth using plants (Fauziah et al., 2024). Other obstacles, such as sensor calibration, data reliability, internet connectivity in remote areas, energy use, and e-waste management, further slow the widespread use of these technologies. This review overcomes these drawbacks by thoroughly analysing the IoT-based NPK sensor systems for precision nutrient management. The review critically discusses existing NPK sensing techniques, calibration methods, IoT architectures, communication protocols, cloud-based platforms, and their use in various crop cultivation systems. In addition, it explores the issues of implementation in the field and summarises the latest advances in AI nutrient management and opportunities for future development with the combination of AI, blockchain technology and autonomous agricultural systems.

The novelty of this review is the interdisciplinary perspective which combines elements of agronomy, sensor engineering, as well as IoT technologies and data science to enable a system-level evaluation of IoT-enabled nutrient management. This review not only compares sensor performance and calibration procedures but also brings together the application of sensors in precision agriculture, the practical problems associated with

their use, and future technological developments, unlike previous reviews that mainly focused on individual sensing technologies or on precision agriculture in general. Hence, the purpose of this review is to provide a comprehensive overview of IoT-based nutrient sensor systems and their contributions to increasing and optimising nutrient utilisation efficiency, sustainable crop production, and global food security.

METHODOLOGY

This review is supported by a structured approach to select the literature to assess the use of IoT-based sensor systems in nutrient management for crop production. Scientific literature relevant to the research was selected using search engines such as Scopus, Web of Science, ScienceDirect, IEEE Xplore, SpringerLink, Wiley Online Library, and Google Scholar (the primary search engine), with a focus on publications primarily from 2017 to 2026. The keywords for identifying the relevant publications were sensor-enabled IoT, NPK sensors, soil nutrient sensing, precision agriculture, sensor calibration, smart farming, nutrient management or combinations of multiple keywords.

The selected literature was analysed and synthesised by theme, including sensor technologies, sensing principles, calibration/validation, IoT architecture, communication technologies, agricultural applications, challenges, future trends, and others. The identified technologies were assessed against one another to identify their strengths, shortcomings, and research gaps, and to highlight opportunities to enhance nutrient management for sustainable crop production via IoT.

COMPONENTS OF IOT-BASED NUTRIENT MONITORING SYSTEMS WITH FUNCTIONS

IoT systems with integrated sensors, microcontrollers and communication modules and cloud-based dashboards enable agriculture to practice real-time site-specific nutrient management.

Nutrient Sensors

Nutrient sensors are an important part of soil analysis and IoT technologies, in particular, those that utilise ion-selective electrodes (ISE) and either optical- or electrochemical-based methods (Figure 1). These sensors analyse soil and report in real time, at an on-site, granular level, on the critical nutrient ions: nitrate (NO_3^-), phosphate (PO_4^{3-}) and potassium (K^+).

Probes constructed from advanced stainless steel, such as those manufactured by Renke Electronics (2024), offer versatility in soil conditions. These sensors and methods have been shown to be suitable for laboratory comparisons, with a low error rate of 8.47% (Musa et

al., 2023). However, the soil conditions consistent with the use of these probes, such as moisture, pH and temperature, should be taken into account to improve the calibration of these sensors (NiuBoL, 2024).

The promising performance of digital technologies and smart fertigation systems (sensors, GPS, GIS, automation, etc.) has yet to be validated for real-world, long-term use for sustainability. Therefore, while the overgeneralised claims pertaining to the soil sensors may indicate reliability, this must be supported with soil-specific calibration for the soil at the impacted sensors.

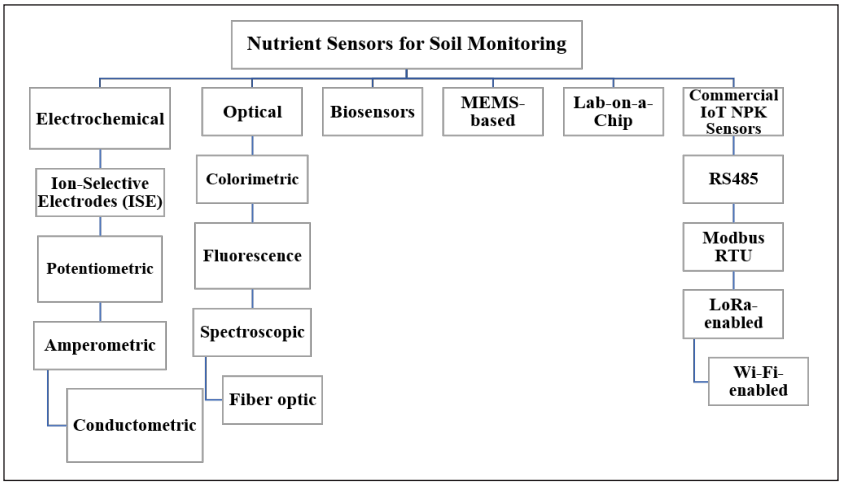


Figure 1. Different types of nutrient sensors used for soil nutrient monitoring

Microcontrollers and Embedded Systems

Microcontrollers such as ESP32, Arduino Uno, and Raspberry Pi (Table 1) function as devices which process data and transmit information (Figure 2). The ESP32 device enables wireless connections with cloud services because it consumes minimal power and includes Wi-Fi and Bluetooth capabilities, which maintain stable analogue-to-digital conversion results (Sudarmaji et al., 2024). The Arduino boards serve as common tools for sensor calibration and prototyping needs, but users must obtain additional modules to achieve connectivity and storage capabilities. The Raspberry Pi system provides advanced computational capabilities that support complex applications involving image-based nutrient-deficiency detection and artificial intelligence analysis (Billa et al., 2023). These controllers establish essential connections between sensor networks and cloud dashboards that operate in real time, enabling decision-making for digital farming operations (Figure 3 and Table 1).

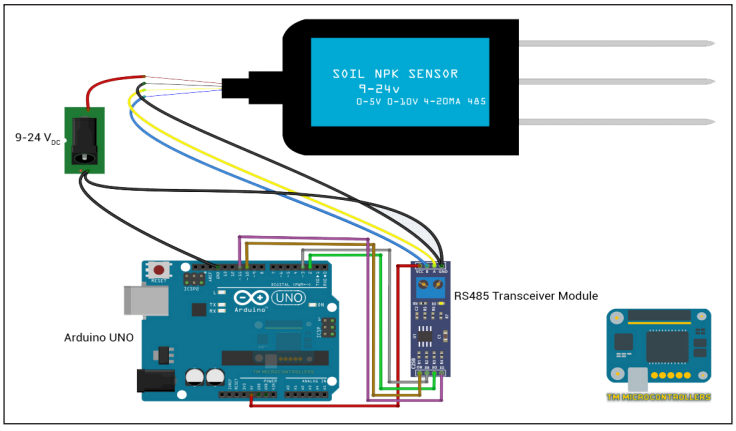


Figure 2. An NPK sensor with Arduino (Teach Me Micro, 2023)

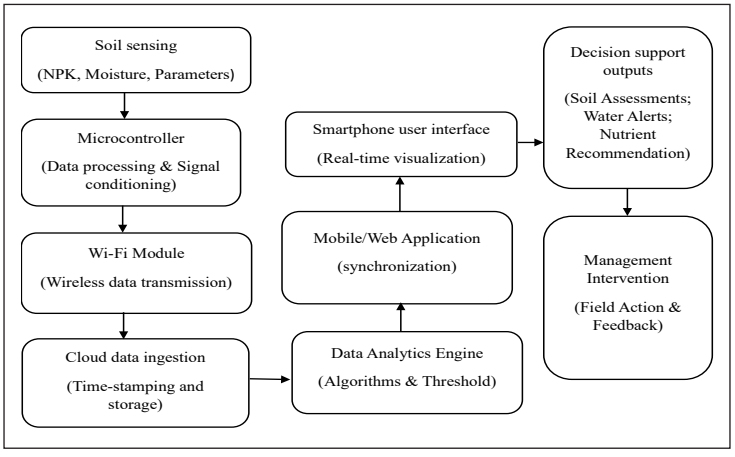


Figure 3. Architecture of IoT-based plant nutrient control system (Anjaneyulu et al., 2024)

Table 1
Information on some controllers utilised by researchers in IoT-based agricultural management

Controllers Name	Function	Authors
NodeMCU ESP8266	Internet access to transmit to ThingSpeak; data is saved in the micro-SD memory and processed.	Karinia et al., 2021; Nofriandi et al., 2023
Thingspeak	Functioned as an IoT cloud platform for receiving, storing, and remotely visualising real-time sensor data on a smartphone	Karinia et al., 2021; Nofriandi et al., 2023;
Arduino-based IoT device	Collects sensor data, processes it, and sends it to the cloud for real-time remote monitoring and control.	Rivas-Sánchez et al., 2019
Raspberry Pi	Used for complex farm IoT systems, enabling fast data processing, device integration, and live monitoring, ideal for large-scale agriculture.	Billa et al., 2023

Table 1 (*continued*)

Controllers Name	Function	Authors
ESP32 microcontroller	A low-cost, low-power device with built-in Wi-Fi and Bluetooth, commonly used in IoT systems to collect data from sensors, process it locally, and transmit it wirelessly to cloud platforms (like ThingSpeak) or mobile devices for real-time monitoring and control.	Idris et al., 2024
LoRaWAN	Facilitates long-distance, low-power wireless communication between IoT devices and gateways, ideal for remote and energy-efficient data transmission.	Arshad et al., 2022

Communications Technologies

Various technologies can be leveraged to achieve wireless data transmission: Wi-Fi in the short range (Table 3), LoRaWAN, Zigbee, and NB-IoT in the long range with low power consumption, etc., of which LoRaWAN in particular is very popular in rural areas of agriculture because it is highly scalable, has a long range (>10 km), and has low power consumption (Augustin et al., 2016). This technology allows several sensors to send data to a central server and is known to perform well in low-signal environments. Studies analysing these technologies in a comparative fashion often refer to their bandwidth, power consumption, and cost as a trade-off of the networks (Kochhar et al., 2019) (Table 2).

Table 2
Performance metrics of WSN (Wireless Sensor Network) communication technologies

Communication Module with Range	Frequency with Data rate	Nodes	Cost & Power	Communication System
Wi-Fi (20-100 m)	2.4 GHz 2-54 Gbps	32 nodes per network	High & High	Access point to the device
Bluetooth (1-100 m)	2.4-2.485 GHz 1-3 Mbps	8 active nodes per piconet	Low & Moderate	Master slave & peer-to-peer
Zigbee (10-20 m)	2.4 GHz 20-250 Kbps	65,000 nodes per network	Low & Low	Peer-to-peer
GPRS (In range of mobile network area)	900-1800 MHz 56-114 Kbps	1000 nodes per network	High & High	Base station to device
LoRa (>10 km)	169 MHz, 868 MHz, 433 MHz 0.3-50 Kbps	10,000 nodes per gateway	Moderate & Low	Peer-to-peer
XStream (5-16 km)	2.4 GHz 10-20 Kbps	7 channels, 65000/channels	Low & Low	Peer-to-peer

Source: Jawad et al. (2017)

Cloud Platforms and Dashboards

Sensors and their associated data can be managed, visualised, and stored on centralised platforms, including ThingsBoard, Thingspeak, Firebase, and AWS IoT. These dashboards provide actionable insights via real-time graphs, alerts, and predictive analytics by processing sensor data (Okhovat & Bauer, 2021). With the help of cloud-based thresholds, farmers and agronomists can optimise the scheduling and amount of fertiliser applications, thereby improving fertiliser NUE and reducing environmental impact (Bhatt et al., 2024). More sophisticated dashboards integrate AI algorithms and historical data processing, enabling the creation of adaptive Decision Support Systems (DSS) that respond to changes in the field.

Sensor Calibration and Nutrient Detection Activities

In the context of continuous nutrient tracking and precision nutrient management for IoT-based NPK sensors, calibration is critical to ensuring their accuracy, reliability, and stability over time. Environmental changes and electronic drift could cause sensor performance to decline over time, which would also affect the accuracy of the measurements they can make (Musanase et al., 2023; NiuBoL, 2025). Traditionally, calibration starts by developing a baseline configuration to stabilise sensor outputs and reduce background noise. The sensor is then put into soil samples or standard nutrient solutions with known concentrations, and an electrical response (voltage, EC, current, or optical absorbance) is measured. The calibration curve is then formed by applying the appropriate regression equation to the sensor response to convert raw sensor data into quantitative nutrient measurements (Ma et al., 2020).

The overall calibration process is common to most NPK sensing systems, but the exact calibration process will vary depending on the sensing technology used. Generally, calibration is the process of comparing sensor measurements with a laboratory analysis or a certified standard solution. Sensor probes should be cleaned before calibration, and electrochemical sensors should be stabilised in standard solutions before use. Base data are then collected under controlled conditions, and systematic differences between the sensor reading and the reference data are eliminated by means of offset corrections or regression analysis-based calibration equations. This is a standardised approach to reduce systematic error and enhance measurement consistency prior to field deployment (Musanase et al., 2023; NiuBoL, 2025).

Calibration Approaches Based on Sensing Technology

The following section summarises the calibration approaches available for the sensing technology. The requirements for calibration vary widely and depend on the measurement

principles of the different sensing technologies. Ion-selective electrode (ISE) sensors measure the activity of nutrient ions directly using the Nernst equation and typically require two-point calibration with standard solutions of known ion concentrations to determine the electrode slope and intercept (Li et al., 2019). To reduce the variation between electrodes and ensure the uniformity of the measurements, advanced ISE systems use baseline correction and two-point normalisation **(**Kim et al., 2013). ISE sensors offer moderate analytical precision and direct measurement of nutrients, but the sensor membranes age, temperatures fluctuate, and ionic interferences require periodic recalibration.

In contrast, some commercially available low-cost RS485 soil nutrient sensors (NPK) measure the electrical conductivity of the soil (EC) indirectly rather than the levels of N, P, and K ions directly (Musanase et al., 2023). In the calibration phase, the EC values obtained from the sensors are first correlated with the EC concentration in the lab, and empirical regression models are then developed to obtain the NPK concentration. This method significantly lowers sensor price and is suitable for field deployment in a short time; however, prediction accuracy is highly dependent on the soil textures, moisture levels, fertiliser compositions, and the calibration data set. Thus, most of the time, EC-based sensors need to be calibrated at the point of use in practical applications.

Optical and colourimetric sensors use a different calibration approach, based on the Beer - Lambert law: changes in light absorbance are used to determine nutrient concentration. Calibration is performed by selecting the wavelengths at which each nutrient exhibits the highest absorbance and by creating calibration curves using nutrient solutions. The absorbance values are then used to fit linear regression models to convert them to nutrient concentrations (Kumbhare & Kumbhar, 2023). Optical sensors typically offer greater analytical sensitivity in the laboratory but generally require additional sample manipulation and are less well suited for continuous in situ monitoring of nutrients.

Environmental factors and soil properties such as moisture content, temperature, pH, soil texture, salinity, organic matter, and ionic interference significantly affect sensor accuracy. These should therefore be taken into account when calibrating to help to ensure more reliable measurements in the field. Of these, soil moisture has one of the most important effects, as it directly affects ionic mobility and electrical conductivity. Calibration is recommended under standard soil moisture conditions in several studies to enhance repeatability and minimise variation in soil moisture measurements (Estrada et al., 2025; Fathima et al., 2026). Similarly, calibration models should be developed independently for each soil texture, as the contents of clay, organic matter, and cation exchange capacity affect the sensor's response. The calibrated models for sandy soils might then not be directly applicable to clay or loam soils without large prediction errors (Fathima et al., 2026). The incorporation of environmental sensors and compensation algorithms to minimise the influence of environmental conditions is also proposed (Postolache et al., 2022).

Furthermore, sensors should be recalibrated every 6-12 months due to sensor drift, membrane degradation, and exposure to environmental factors for extended periods of time (NiuBoL, 2025). Depending on the characteristics of the sensor's response, the relationship between the sensor's output and the nutrient concentration can be modelled using an appropriate regression model. If the sensor output is approximately proportional to the nutrient concentration, a linear regression can model the relationship between them (Jaja et al., 2026).

A linear calibration model is often used when the sensor response is proportional to the nutrient concentration, as in Equation 1:

$$Y = AX + B \quad [1]$$

where X is the raw sensor reading, Y is the nutrient concentration of the solution, A is the calibration slope, and B is the offset. If the sensor response is nonlinear, a second-order polynomial regression model can be used to improve the calibration relationship. A general nonlinear calibration relationship is given as in Equation 2:

$$C = a + bV + cV^2 \quad [2]$$

where C is the nutrient concentration measured in mg kg^{-1}, V is the sensor voltage or absorbance response, and a, b and c are regression coefficients derived from curve fitting.

The simplicity and high coefficient of determination under controlled laboratory conditions make linear regression a commonly used method (Fathima et al., 2026; Li et al., 2019). Soil is a heterogeneous medium, and a number of non-linear relationships are common due to variations in moisture, salinity, and texture. Therefore, second- or third-order polynomial regression models tend to yield more accurate calibrations for complex soils, especially for potassium estimation (Estrada et al., 2025).

Polynomial regression can be used to enhance the calibration model when the sensor's output is nonlinear (Jaja et al., 2026). This model can be written as in Equation 3:

$$Ci = \beta_0 + \beta_1 Vi + \beta_2 Vi^2 + \varepsilon i \quad [3]$$

where Ci is the concentration of the nutrient measured (mg kg^{-1}), Vi is the sensor signal for the nutrient, β0 is the intercept, β1 and β2 are regression coefficients, and εi is random error.

Once the regression coefficients are obtained using least-squares fitting, the resulting model can be used in the future to estimate nutrient concentrations in real time based on sensor measurements. The statistical measure of the coefficient of determination (R2) is usually used to assess calibration performance, as in Equation 4:

$$R^2 = 1 - [\Sigma (C_i - \hat{C}_i)^2 / \Sigma (C_i - \bar{C})^2] \quad [4]$$

This is done using the measured nutrient concentrations C_i, the predicted nutrient concentration with the calibration model $\hat{C}_i$, and the mean measured concentration $\bar{C}$. Numbers closer to 1 indicate greater agreement between predicted and measured values. Other indicators of performance that are often used to measure the accuracy of predictions and the robustness of the model include root mean square error (RMSE) and mean absolute error (MAE).

Calibration is crucial to these validation methods, as accurate interpretation of sensor readings and precision fertiliser management decisions rely on a reliable calibration. It has been shown that low-cost sensors that have been calibrated to detect soil nutrient availability can be used to detect spatial and temporal changes with good accuracy when compared with laboratory analysis. For instance, a 5-pin RS485 sensor was used to successfully measure soil nutrient variability and yielded nutrient measurements consistent with laboratory methods, thus serving as a reliable tool for making fertiliser management decisions (Musanase et al., 2023). Likewise, models generated by correlating electrochemical and optical sensor responses with laboratory-derived nutrient data have estimated the availability of soil nutrients (N, P, K) in real time with high predictive accuracy (Sulaeman et al., 2024).

Appropriate agronomic nutrient thresholds are also needed for the interpretation of calibrated sensor measurements. They are the lowest nutrient concentration needed to prevent nutrient deficiencies and to promote maximum crop growth. No recommendations were made for this nutrient in rice production because the concentrations found in most soils are generally above the lowest levels generally correlated with nutrient deficiency (about 30 and 110 mg kg^{-1} for nitrogen and available potassium, respectively). The range of leaf nutrient concentrations of ~2.5% N and ~0.10% P are also critical for healthy plant development. The desirable nutrient levels in Malaysian rice soils are total N 0.22%, available P 31 mg kg^{-1}, and exchangeable K 0.29 cmolc kg^{-1} (Panhwar et al., 2023). Using calibrated sensor output with these agronomic thresholds can develop decision-support algorithms that provide site-specific fertiliser recommendations.

Overall, calibration is one of the most important factors affecting the performance of NPK sensors used in IoT. However, there is no consistent calibration protocol because calibration varies with the sensing technology used, soil characteristics, and environmental conditions. ISE sensors have high analytical accuracy and are used less frequently, whereas EC-based sensors are more costly and are better suited to large-scale applications but rely heavily on site-specific calibration models. Optical sensors offer high laboratory precision but are less useful for continuous field monitoring. Adaptive calibration techniques with environmental compensation algorithms and machine learning methods should therefore

be explored in the future to achieve higher sensor accuracy over the long term, decrease calibration frequency, and make the use of nutrient-sensing systems in IoT more feasible in precision agriculture.

APPLICATIONS IN PRECISION AGRICULTURE

By enabling site-specific, real-time, and data-driven nutrient management techniques, the integration of IoT-based nutrient monitoring systems is transforming precision agriculture. Across the diverse cropping systems, these technologies provide better decision-making and improve fertiliser use efficiency.

Site-Specific Nutrient Management (SSNM)

Site-Specific Nutrient Management (SSNM) greatly improves nutrient supply efficiency by reducing the variations in nutrients, which are both spatially and temporally distributed. The IoT soil sensors, which come with GPS and data analytics integration, identify the real-time NPK levels in very small zones, thus allowing the delivery of nutrients according to need. These data are used to create SSNM maps and field-specific fertiliser plans that lead to higher nitrogen uptake and assimilation (Dobermann et al., 2002). According to Buresh et al. (2010), real-time sensing is a powerful way of recovering nutrients. NPK sensors in Figure 4 can determine the nutrient concentrations by three methods: electrochemical, conductivity, or optical. The electrochemical method identifies NO_3^-, PO_4^{3-}, and K^+ ions using selective ion electrodes and simultaneously establishes a relationship between ion concentration and electrical potential (Table 3). EC (Highly Conductive Soil) is connected to nutrient content through conductivity techniques (Renke Electronics, 2024; NiuBoL, 2024), and optical methods work by measuring reflectance in the visible and NIR spectral regions (Adhikary et al., 2024).

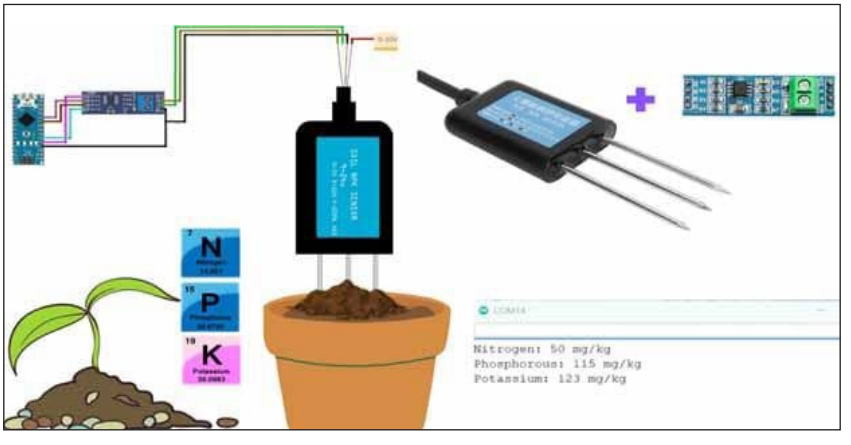


Figure 4. A pictorial view of an IoT-Enabled soil NPK sensor system (Saleem et al., 2024)

Table 3
Technical specifications of an IoT-enabled 8-in-1 soil nutrient sensor system

Parameter	Range/Description	Accuracy %
Communication Module	RS485	-
IoT Module	ESP8266 WiFi-enabled circuit	-
Cloud Integration	Jiousu IoT Cloud Server (CSV export, real-time monitoring, analysis, and visualisation)	-
Supply Voltage	DC 5 - 24V	-
Power Consumption	15 mA @ 12 V DC	-
Baud Rate	9600 bps	-
Temperature Range	−40 °C to 85 °C	±1.0 °C
Soil Moisture Range	0% to 100% (Relative Humidity)	±5%
Electrical Conductivity	0 to 10,000 µS/cm	±5%
Nutrient Range (NPK)	Nitrogen (N): 0 - 200 mg kg^{-1} Phosphorus (P): 0 - 200 mg kg^{-1} Potassium (K): 0 - 200 mg kg^{-1}	±10%
pH Range	0 to 14	±10% (precision)
Salt (Salinity) Range	0 to 10,000 µS/cm	±5%
Response time (NPK; EC)	<1s	

Source: Shahab et al. (2025)

There are also hybrid sensors that measure humidity, pH, and temperature along with nutrients for better accuracy (Musa et al., 2023). The sensor's output data are corrected using algorithmic or machine-learning models to determine nutrient levels, their distribution, and sufficiency (Chen et al., 2025). The real-time data from the IoT sensors are sent to the cloud, where they help in the decision-making process for the site-specific fertiliser application. This approach not only improves nutrient use efficiency but also reduces losses and maintains yield (Adhikary et al., 2024; Chen et al., 2025).

Real-Time Fertiliser Scheduling

Real-time sensors integrated into IoT systems have made it possible to monitor nutrient demands dynamically and optimally apply fertiliser s accordingly for the entire crop cycle. For example, nitrogen supply can be adjusted based on the crop's developmental stage and data from chlorophyll or soil nitrate sensors. This method eliminates the problem of fertilising too much and guarantees proper and on-time nutrient delivery to the plants, particularly in the case of the most demanding ones like rice and maize. IoT platforms enable remote fertigation monitoring and management, along with control of settings; if any parameters exceed thresholds, alerts are triggered (Idris et al., 2024). The use of IoT technology for nutrient tracking mitigates the possibility of nutrient imbalances and ensures the production of healthy crops. NPK sensors, which can be conductivity, optical, or ion-selective (Table 4), implement the detection of nutrients (Renke Electronics, 2024).

Accuracy has been improved by using hybrid sensors that account for both pH and moisture data (Musa et al., 2023). The raw data collected are calibrated and corrected based on environmental conditions such as temperature and salinity (NiuBoL, 2024). Such monitoring, when maintained continuously, can show when there is a nutrient shortage and suggest fertilisers of a particular type and at the right amount on the spot instantly (Adhikary et al., 2024), thus making it easier for them to be retained in the soil and at the same time preventing losses caused by leaching or volatilisation (Musa et al., 2023).

Table 4
Some nutrient measuring technologies in IoT-based nutrient management system

Technologies	Advantages	Disadvantages	Representative Authors
Ion-Selective Electrodes (ISEs)	Direct ion measurement (NO_3^-, NH_4^+, K^+); Real-time output, Low power, easy IoT integration, Inexpensive; Response time: seconds to minutes; Moderate robustness	Signal drift requires frequent calibration• Temperature and interfering ion sensitivity; membrane fouling; limited selectivity for some nutrients	Morawska et al., 2024
Optical Spectroscopy (UV-Vis, MIR, NIR, Fluorescence)	Non-destructive; multi-nutrient detection; fast & high throughput; moderate to high cost; Response time: seconds to minutes; moderate robustness	Affected by soil moisture & texture; requires calibration models and indirect nutrient estimation	Qi et al., 2024
Electrochemical Impedance Sensors	Low cost; sensitive to ion variations; Moderate robustness; Typical accuracy moderate-high; Suitable for in situ	Influenced by soil salinity & moisture; requires site-specific calibration	Manjushree et al., 2024
Chlorophyll Meters (SPAD)	Fast, non-destructive; good for N assessment; robustness is high under consistent crop growth	Indirectly affected by leaf thickness and stress; cannot measure P, K	Ali & Saleem, 2024
Soil EC, pH, and Moisture Sensors	Low cost; essential for nutrient availability; Typical accuracy high; Robustness high	Indirectly affected by soil salinity; cannot directly measure NPK	Idris et al., 2024
Biosensors (Enzyme/ Microbial Sensors)	High specificity for nitrate/ phosphate; lower drift for ISE	Limited robustness in field soil; higher cost and stability issues; Short biological lifespan	Sonowal et al., 2025
Nano-Sensors (CNT, Graphene, Metal Oxide)	Ultra-high sensitivity; fast response time; can be made flexible; Moderate robustness	Expensive fabrication; Field durability is still limited; commercialisation still limited	Yadav et al., 2023
IoT-Linked Fertigation Sensors (EC/pH/ Flow)	Automated nutrient delivery; real-time control; Typical accuracy is high with high robustness	High installation and maintenance costs; Requires periodic calibration	Sood et al., 2025

Integration with Variable Rate Technology (VRT)

Using Variable Rate Technology (VRT) in combination with AI is an emerging trend in precision agriculture that is undeniably beneficial, particularly in applications where fertiliser is used. VRT is the combination of crop seed, agrochemicals, and soil characteristic maps (Rokhafrouz et al., 2021). VRT uses sensor-based (real-time feedback) and map-based (prescription maps) methods. VRT is enhanced with IoT-generated nutrient maps, particularly for automating site-specific fertiliser applications. VRT technology can optimise fertiliser rates and adjust them to improve crop yield and nutrient use efficiency (NUE) in wheat and maize (Khosla et al., 2008). Using VRT, a range of fertiliser (12.59-50.41 kg/ha) was successfully adjusted based on driven shaft speed and sensor height (40-100 cm) at varying stages of rice growth. NDVI improved, and sensor-based VRT was able to reduce the use of nitrogen (Mirzakhaninafchi et al., 2022).

The NPK sensors that measure soil nitrate, phosphate, and potassium (Eldeeb et al., 2023) using ion-selective and electrochemical methods are part of this system (Table 5). These measurements, taken in conjunction with geo-referenced GPS, form the basis of the nutrient maps. Variable-rate applicators, in conjunction with GPS, adjust to changes in the device and improve efficiency in the use of one or more fertilisers (Musa et al., 2023). The use of integrated, data-driven systems supports adaptive and sustainable nutrient management.

Case Examples in Major Crops: Rice

IoT enables real-time nutrient monitoring, which has altered the best methods of precision agriculture, especially rice farming. When these systems are paired with soil and water sensors, they help provide accurate split nitrogen (N) applications, which reduces nitrogen losses and improves nitrogen left in grain yields. NDVI readings (Table 6) for rice indicate this, shifting from 0.49 to 0.69 as nitrogen levels increase from 75 to 225 kg/ha. This demonstrates enhanced crop vigour through sensor-based variable-rate technology (Mirzakhaninafchi et al., 2022). The system demonstrated its efficacy with sensor heights (40 - 100 cm) and rice growth stages, helping achieve 45% savings in fertiliser input. The combination of monitoring parameters (soil temperature, moisture, EC, pH, and nutrients) has shown positive effects on crop growth. In Pakistan, an IoT-based rice system enabled real-time management of crop parameters, improving productivity (Shahab et al., 2025). Controlled fertigation management improved water-use efficiency by 64%, increased crop yield by 35%, reduced weed growth, and reduced nutrient leaching. Drip fertigation helps to increase nutrient use efficiency by up to 29% and enhances water use efficiency by 70% (Singh & Singh, 2026).

Table 5
Some related research work on nutrient sensor detection system

Authors	Echnology Involved	Purpose of the Study	Major Findings	Research Gap
Bristow et al., 2022	Ion-selective electrode (nitrate ISE) linked with LoRaWAN IoT node	To develop and validate a soil nitrate sensor node for real-time field monitoring and cloud reporting	Validated real-time nitrate monitoring with LoRaWAN; effective for fertiliser decision support	Long-term field trials and multi-ion (full NPK) integration are not shown
Eldeeb et al., 2023	Potentiometric ISE (TDDA nitrate)/electrochemical array	Fabricate a selective nitrate ISE for in-situ soil measurement	Demonstrated the high nitrate selectivity and in-soil applicability	Sensor drift and long-term stability in diverse soils need more assessment
Catini et al., 2022	Lab-on-a-chip (microfluid) colorimetric platform (automated reagent mixing)	Build an automated LOC platform for continuous colorimetric nutrient assays (nitrite/nitrate)	Demonstrated automated, continuous colorimetric assays with low reagent use; suitable for in-field deployment	Robustness and reagent cartridge lifetime for long deployments require improvement
Clinton-Bailey et al., 2017	Microfluidic LOC for in-situ phosphate (improved "phosphate blue" assay)	In situ measurement of soluble reactive P with a microfluidic analyser	Lab-grade phosphate assay miniaturised for field use; good sensitivity and autonomy	Integration into multi-analyte (NPK) platforms and ruggedisation for soils remains needed
Baumbauer et al., 2022	Printed potentiometric nitrate sensors (inkjet-printed ISEs)	Produce low-cost, printable nitrate sensors for soil monitoring	Printed sensors showed practical sensitivity and could be mass-fabricated affordably	Field lifetime, reference electrode stability, and multi-ion capability need work
Lal et al., 2023	Electrochemical & optical sensors for nitrate	Review field-deployable nitrate sensing technologies and suitability for agricultural monitoring	Electrochemical and optical methods are promising for field nitrate sensing; they highlighted trade-offs between cost, accuracy, and field robustness	General need for standard field validation protocols and multi-parameter integration
Hossain, 2024	Electrochemical sensors (nanoparticles, graphene) for nutrients	Survey recent electrochemical developments for nutrient (NPK) detection across water/ soil samples	Advances in nano-materials (CuNPs, graphene) improved sensitivity and selectivity	Few studies demonstrate long-term, in-soil operation across varying matrices (soil, salinity, moisture)
Xu et al., 2024	Graphene ISFET / transconductance-based nitrate sensor	Develop an ultra-sensitive graphene ISFET for nitrate detection	Achieved ultra-low detection limits and fast response for aqueous nitrate	Translation from aqueous proof-of-concept to heterogeneous soil measurement and fouling mitigation is needed

Table 6
Accuracy percentage of different agricultural sensor technologies for soil and crop monitoring

Description	Parameter	Accuracy (%)	References
DHT11 + NodeMCU ESP8266 + an on/off switch + a reset button	Soil temperature and Humidity	99.93% and 99.95%	Nofriandi et al., 2023
SHT11 + NodeMCU ESP8266 + Arduino Uno + an on/off switch + a reset button + SD card	Soil moisture	99.95%	Karinia et al., 2021
NDVI sensor	Crop canopy reflectance	0.83% to 4.92% system error in fertiliser application	Mirzakhaninafchi et al., 2022
NPK sensor	Nitrogen, Phosphorus, Potassium	Error rate: 8.47% compared to laboratory control sensors Accuracy approx.: 91.53%	Musa et al., 2023

IoT systems for maize help address fluctuations from pests such as the Fall Armyworm and irregular rainfall (Aruna Balla et al., 2019). In Nigeria, IoT-supported climate monitoring has shown promise for year-round maize production (Nwankwo et al., 2019).

The introduction of IoT into wheat cultivation has enabled top-dressing N based on canopy reflectance readings and real-time soil nitrate rates, thereby improving N recovery efficiency through optical sensing (Raun et al., 2002). The sprinkler system based on IoT enhanced efficiency in saving water (55%), and it saved 25% of fertiliser by optimising irrigation and fertilisation timings, respectively, according to the stage of wheat growth and soil moisture levels. The system implementation resulted in better and more accurate wheat production (Kumar & Choudhury, 2022). Through this approach, wheat crops can achieve higher quality, such as higher protein content, which is a market necessity (Singh et al., 2025).

Using IoT fertigation systems in horticulture, nutrient runoff decreased by 30%, and the eggplant harvesting process was accelerated with minimal fertiliser (Idris et al., 2024). The use of NPK sensors in hydroponics has proven to be effective as IoT systems have provided remarkable improvements in growth and metrics in red spinach and pak choi, as well as significant increases in plant height, biomass and leaf area (Sania et al., 2025).

BENEFITS OF IOT-BASED NUTRIENT MANAGEMENT

Improved Nutrient Use Efficiency (NUE)

IoT devices provide site-specific fertiliser application, supplying nutrients just where and when needed by enabling real-time, high-resolution monitoring of soil NPK levels and supplementary factors, such as moisture and pH. This significantly increases nutrient uptake by crops and minimises waste, effectively improving NUE. IoT-driven decision support

platforms empower farmers to make these precision interventions reliably (Shahab et al., 2025). The system, in short, helps determine the minimum required fertiliser application, thereby reducing excessive and unnecessary fertiliser use, promoting cost savings, and minimising environmental damage (Anjaneyulu et al., 2024). According to the research findings, when put together, the total application of fertilisers was reduced by 45% compared to a conventional blanket area, which was a manifestation that the system was cost-effective and environmentally safe (Mirzakhanafchi et al., 2022). The use of IoT to encourage smart farming contributed to the reduction of the environmental impact by avoiding the excessive use of fertiliser, as well as encouraging sustainable farming (Sahab et al., 2025).

Yield Optimisation and Input Cost Reduction

Using IoT-informed nutrient management can improve crop yields by 15% to 30% and reduce fertiliser use by 10% to 40%, thereby significantly reducing costs (Mirzakhaninafchi et al., 2022). When combined with decision-support systems and variable-rate technology, a 45% reduction in fertiliser use compared to traditional methods was achieved. Real-time monitoring of soil health is made possible by low-cost multi-sensor nodes that track pH, EC, moisture, temperature, and NPK. Machine learning and IoT analytics help to determine the optimal nutrient requirements and the best planting dates for the crops, based on historical soil conditions and weather data (Shahab et al., 2025). Such systems can further reduce fertiliser use by 20% to 40% and water use by 50% (Shahab et al., 2025; Thelkar et al., 2025), while promoting environmental sustainability and reducing runoff.

Environmental Impact Mitigation

Paying attention to how the use of resources is managed through IoT in the context of environmental performance in the reviews of sustainable agriculture is critical. IoT systems provide real-time information on soil nutrient availability, enabling precise fertiliser application to avoid nutrient leaching (Anjaneyulu et al., 2024). In this way, the health of the soil is achieved, and pollution of water systems due to fertilisers, which are often responsible for eutrophication, is limited. Farmers who use only the required amount of NPK are said to help the environment while sustaining the health of the crops (Shahab et al., 2025).

Improved Soil Health and Long-Term Sustainability

Farmers can tailor their fertiliser application to real soil conditions with NPK sensors instead of applying fertilisers based on guesswork. This approach can increase crop production, reduce environmental impacts, and conserve resources. With constant monitoring of the

sensors, farmers will be able to make adjustments to their soil management practices, along with the nutrient compounds, pH level and organic content of their soil. With continuous monitoring, farmers can also intervene before these issues become problematic, along with erosion, salinity, and contamination (Zeptogreens, 2025). Well-distributed and balanced nutrient management will promote soil fertility, sustain agriculture to meet increasing food needs, and protect the environment (Adak, 2025).

Scalability and Adaptability Across Different Farming Systems

Nutrient management sensors can be used on large commercial farms as well as smallholder farms. They can be used on any type of farm because of their sturdy, all-weather construction. Integrated with advanced algorithms and machine learning, these sensors respond to various environmental factors, including weather, soil type, and crop growth. With their innovative sensing technology, farmers receive accurate data on their soil and crops in real-time, which assists them in making better management decisions (Adhikary et al., 2024).

Water-Nutrient Balance

When NPK sensors are combined with the soil moisture monitors, the farmers can examine the interaction of water and nutrients in their fields to a much better degree. Both nutrients and water should be properly managed in order to increase the crop yield and, at the same time, save on resources.

Enhanced Decision-Making for Farmers and Agronomists

The advanced NPK sensors can provide real-time farm soil nutrient data, allowing farmers to apply the right quantities of fertiliser s at the right time. By increasing agricultural production, minimising the impacts on the environment, and reducing the process of overfertilisation, it ensures environmental and economic sustainability (Zeptogreens, 2025). The information provided by sensors helps farmers make informed decisions in crop planning and fertilisation, enabling them to achieve long-term productivity and sustainable agriculture.

CHALLENGES AND LIMITATIONS

Nutrient management systems based on IoT have a number of limitations to their use, particularly when using them in fields:

Sensor Calibration and Soil Heterogeneity

In agriculture, IoT-based NPK sensors are used; however, IoT requires some technical knowledge to ensure accurate data and operations (Van Deursen & Mossberger, 2018). Farmers must receive training to learn how to operate and maintain these devices. Unlike cheaper sensors that have no calibration, more expensive systems have to be recalibrated consistently to provide accurate measurements in different environments (Miller et al., 2025). There are many types of soil, each with varying levels of pH, salinity, and organic matter. All of these factors complicate nutrient sensing, necessitating customisation to a particular field. Without proper recalibration, sensors may report false data, which can lead to harmful nutrient applications. As a result, many farmers lack the expertise needed to use technology more effectively (Musa et al., 2023).

Data Reliability and Sensor Drift

Several researchers have mentioned possible challenges with the storage, processing, and analysis of the vast quantities of data collected by sensors in IoT-based farming (Dash et al., 2019). The misuse of farmers' data would become a breach of farm privacy, so it would be important to implement data protection and security. Pierce & Nowak (1999) describe cases of data drift with cheap sensors, as environmental changes require frequent recalibration. Limited large-scale real-world testing makes it difficult to assess the effectiveness and functionality of these sensors (Fauziah et al., 2024). The flexibility and productivity of wireless sensor networks are backed by strong data protection and solid analytical governance to enhance the trust of farmers (Musa et al., 2023).

Connectivity in Rural Settings

Challenges exist around IoT Reliability, especially for remote internet connections. Weak and intermittent connectivity are particularly problematic for real-time data transfer and monitoring (Tyagi & Sreenath, 2021). Poor infrastructure limited wireless communication (cellular, Wi-Fi, or LoRaWAN), and inadequate precision farming decision-making are all interrelated problems (Wolfert et al., 2017). Furthermore, it can be difficult to gauge practical feasibility because large-scale field trials are still limited (Fauziah et al., 2024). That said, data on nutrients can be captured in real time and uploaded to scalable cloud solutions for remote access and monitoring, such as Google Firebase (Anjaneyulu et al., 2024).

Cost and Accessibility for Smallholder Farmers

Farming technology faces several hurdles, especially in developing nations, due to high setup costs and ongoing system maintenance for things like sensors, gateways, and cloud

technology (Banerjee, 2019). Financial system burdens, coupled with insufficient digital skills, hinder IoT integration. In an effort to address these burdens, farmers can receive alerts and other feedback through mobile apps, such as those designed with the Nodular API, increasing accessibility (Anjaneyulu et al., 2024). In addition, cloud services, predictive analytics, and artificial intelligence enhance user experience and contribute to overall scale (Sahab et al., 2025).

E-Waste

One of the products of agricultural technologies is electronic trash (e-waste), e.g., NPK sensors. When hazardous materials leak into soil and water, they can contaminate the environment and pose health risks because these materials have limited lifespans and high rates of degradation (Adhikary et al., 2024; The Engineer, 2025).

FUTURE PROSPECTS AND INNOVATIONS

Integration with "Artificial Intelligence"/ "Machine Learning" for Predictive Analytics

Artificial Intelligence (AI) and Machine Learning (ML) algorithms now function as essential components of predictive nutrient management models in IoT systems. The models use sensors to analyse current environmental conditions to predict soil nutrient changes, provide fertiliser application recommendations, and help identify nutrient deficiencies at an early stage (Eze et al., 2025). Site-specific nutrient management, crop productivity, efficient use of resources, and reduced environmental impacts are achieved with supervised machine learning based on soil moisture, pH, and nutrient data to accurately predict fertiliser application needs (Narayanan et al., 2026).

Blockchain for Traceable and Transparent Fertiliser Management

Blockchain technology enables transparent nutrient input tracking while ensuring complete accountability through its secure documentation process, which verifies all fertiliser supply and application operations (Banerjee, 2019; Pang et al., 2024). The combination of blockchain technology with IoT systems enables users to monitor fertiliser information in real time, including tracking the specific type and amount of fertiliser and the application time, while establishing an unchangeable record that enables both traceability and sustainability compliance verification.

Remote Sensing and Drone Integration

The combination of drone imaging technology and satellite remote sensing systems together with IoT-based in-situ sensor networks enables farmers to monitor their crops from multiple distances. The combination of high-resolution NDVI (Normalized Difference Vegetation Index)

and chlorophyll content measurements from aerial platforms with ground-level NPK data enables researchers to identify spatial nutrient deficiencies with higher accuracy (Vashishth et al., 2024). The system enables farmers to apply fertiliser s only to specific areas, which leads to reduced fertiliser application and improved nitrogen use efficiency. Low-altitude UAS provide a new and flexible, low-cost and high-resolution platform for precision agriculture; however, they need to be standardised and processed further to ensure precise use (Zhang & Kovacs, 2012).

Autonomous Nutrient Management Systems

Next-generation agricultural systems are moving toward autonomy by merging IoT infrastructure with robotics, AI/ML, and real-time decision engines. The autonomous fertiliser sprayers and drone-based nutrient applicators use sensor data to perform targeted fertilisation without any need for human operators. The systems use closed-loop feedback mechanisms to achieve three benefits, which include better application efficiency, decreased need for workers, and minimised environmental hazards.

Next-Generation Sensors: Bio-Sensors and Nano-Sensors

Scientists have developed highly sensitive biosensors which use nitrate reductase enzymes to measure nutrient content in soil and plant samples. The sensors deliver immediate nutrient feedback when they connect to IoT platforms, which enables users to take quick action. Nano-sensors that use graphene and carbon nanotube materials demonstrate excellent sensitivity because they can detect very small amounts of essential ions, while their components can be made into small and flexible sensor systems (Yadav et al., 2023). The technologies provide excellent potential for developing affordable portable devices that can frequently monitor nutrient levels. Future researchers can use this type of sensor and also multi-nutrient sensing.

Biodegradable and Ultra-Low-Power Sensor System

The necessity of analytics ecosystems to incorporate environmentally responsible approaches is further necessitated by the expanding scope of IoT in agriculture. Degradable sensors, made of fully biodegradable materials, as opposed to traditional electronics, support the reduction of e-waste and offer an eco-friendly alternative (Matiieshyn, 2025). Ultra-low-power sensor nodes, allowing intermittent data collection and transmission, will provide increased longevity of the devices while preserving data fidelity. These developments reflect the heightened interest in cost-effective device longevity and energy- and environmentally sustainable designs in agricultural monitoring systems (Zahedi et al., 2024).

Cybersecurity and Data Privacy

As NPK sensor systems become more integrated through wireless networks and cloud-based systems, cybersecurity and privacy will be major concerns. Going forward, the need of the hour is to focus on developing secure communication protocols, data encryption techniques, authentication, and intrusion detection systems to ensure that sensor networks are not subjected to cyber-attacks and unauthorised access. The safety, confidentiality, and availability of sensor data are crucial for accurate decision-making in precision agriculture. Further, adequate cloud storage solutions and privacy-enhancing data-sharing mechanisms need to be developed to boost farmer trust and facilitate the adoption of smart farming solutions.

Large-Scale Field Implementation

Very little literature has examined the IoT-enabled NPK sensor in real farming environments, as most studies have been conducted in lab settings or under small-scale experimental conditions. Future work needs to focus on large-scale, long-term field testing in various soil types, climates, cropping systems, and management strategies to more accurately test the performance of sensors in real-world agricultural applications. In addition, detailed economic evaluation (including cost-effectiveness, maintenance, scalability and farmer adoption) must be done to determine the commercial viability of such technologies. These studies will enable the adoption of NPK sensor-based IoT systems from the research lab to commercial precision fertiliser management.

CONCLUSION

IoT-based nutrient management systems represent an innovation in smart farming, enabling real-time monitoring and data-driven decision-making that strengthen NUE, crop productivity, and environmental sustainability. The incorporation of NPK sensor-based monitoring successfully identified changes in soil nutrients in real-time, allowing for accurate and timely fertiliser administration. By reducing losses and matching crop nutrient needs, this strategy greatly increased fertiliser usage efficiency. As a result, rice yield and the yield performance of other crops increased under sensor-data-driven optimised fertiliser schemes. Current research has yet to carry out large-scale, long-term field validations for sensor accuracy, system reliability, and economic feasibility in diverse agricultural conditions, particularly for smallholder farming systems. The broader adoption is still being hindered by challenges with sensor calibration, rural connectivity, and affordability. Collaboration between agronomists, engineers, data scientists, and policymakers is necessary to achieve a scalable impact. Future research should prioritise the development of reliable, low-cost, and intelligent IoT-based NPK sensing systems

integrated with artificial intelligence and decision-support tools for climate-resilient and sustainable crop production.

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Biofertiliser Application of PGPR *Pseudomonas aeruginosa* AGKT1 Enhances Nitrogen, Phosphorus, and Potassium Availability in the Potting Mixture of Oil Palm Seedlings

Shah Ahmed Reza[1], Md Kamal Uddin[1]*, Susilawati Kasim[1], Ali Tan Kee Zuan [2], Sriharan Raguraj[3], and Effyanti Mohd Shuib[1]

[1]Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia (UPM), 43400 Serdang, Malaysia

[2]UDRP – Regenerative Agriculture for Sustainable Crop Productivity, d/a Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, Serdang, Selangor, 43400, Malaysia.

[3]Soils and Plant Nutrition Division, Tea Research Institute of Sri Lanka, 22100 Talawakelle, Sri Lanka

ABSTRACT

Concerns over environmental consequences and sustainability issues regarding the overuse of chemical fertilisers in the oil palm industry have prompted the search for a biofertiliser alternative. This study explores the efficacy of a novel biofertiliser formulation containing *Pseudomonas aeruginosa* AGKT1, alone and in combination with chemical fertiliser (NPK 15:15:15), on soil nutrient availability and microbial activity in potting mixtures used to raise oil palm seedlings (*Elaeis guineensis*). A randomised complete block design (RCBD) assessed eight treatments replicated thrice over four months. Results were analysed using one-way ANOVA and mean comparisons via the LSD test. Treatment T4 (100 mL biofertiliser alone) yielded the highest microbial population (8.91 log CFU/mL), total N (0.29%), total soil phosphorus (353 mg/kg), available P, and Zn, reflecting a strong capacity for nutrient solubilisation. Meanwhile, T7 (100 mL biofertiliser + 50% NPK) recorded the highest soil magnesium (40.55 mg/kg) and available phosphorus (34.86 mg/kg), alongside strong total N performance, identifying it as the most efficient integrated option. The results clearly demonstrate the potential of the newly formulated biofertiliser inoculated with *P. aeruginosa* AGKT1 in nutrient solubilisation when applied alone and combined with chemical fertiliser, establishing it as a sustainable supplement for chemical fertilisation in oil palm cultivation.

Keywords: Microbial population, nutrient availability, oil palm, *Pseudomonas aeruginosa AGKT1*, potting mixture

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E-mail addresses:
rezashahahmed@gmail.com (Shah Ahmed Reza)
mkuddin07@gmail.com (Md Kamal Uddin)
susilawati@upm.edu.my (Susilawati Kasim)
tkz@upm.edu.my (Ali Tan Kee Zuan)
raguraj90@yahoo.com (Sriharan Raguraj)
effyantims@gmail.com (Effyanti Mohd Shuib)
* Corresponding author

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INTRODUCTION

Oil palm occupies a prominent position in the agricultural sector and has scientific importance, especially in the tropical regions of Southeast Asia, Africa, and South America (Woittiez et al., 2017). This exceptional crop species is widely recognised for its many contributions to global agricultural and commercial sectors, as well as its significant role in scientific research aimed at enhancing our understanding of novel breeding techniques (Parveez et al., 2020; Qaim et al., 2020; Siddiqui et al., 2021). Malaysia has 5.87 million hectares of land under oil palm agriculture. In 2020, Malaysian export revenue increased (8.40%) to RM64.84 billion from the previous year (Mohamad et al., 2023). Biological control-based technology can be used as a good way to improve soil quality and increase its nutrient productivity, including essential nutrients needed for plant growth (Mahmud & Chong, 2021). Microbial biofertilisers represent a crucial facet of sustainable agriculture, achieving the dual goals of nutrient enrichment and disease suppression in soil (Duhan & Kataria, 2022). Enhanced soil nutrient pools, including organic carbon and a range of macro- and micronutrients, were observed under integrated application of microbial biofertiliser combined with reduced chemical fertiliser inputs, indicating an overall improvement in soil fertility status (Roslan et al., 2025). Additionally, this practice has proven to enhance the absorption of nutrients by the oil palm seedlings and improve the overall nutrient status of the soil (Ajeng et al., 2020). The oil palm seedlings that were subjected to a treatment involving the combination of a consortium of microorganisms and 30% chemical fertiliser exhibited superior growth performance and nutrient content when compared to the control treatments (Keni et al., 2023).

Different microorganisms can solubilise distinct micronutrients. Bacteria such as *Pseudomonas* spp. comprise several strains that can employ various mechanisms to solubilise multiple micronutrients (Nadeem et al., 2016). In previous studies, the strain Pseudomonas aeruginosa AGKT1 was found to fulfil all the necessary criteria as a promising microorganism for preparing biofertiliser (Basu et al., 2021; Duhan & Kataria, 2022; Timmusk et al., 2017). This strain not only improves nutrient absorption through fixation and solubilisation, but also synthesises phytohormones and organic acids, which are beneficial for plant growth (Parvin et al., 2020). *Pseudomonas* spp. is one of the widely studied plant growth-promoting rhizobacteria which enhance the availability of important soil nutrients required for plants (N, P, K, Zn, Fe) and improve plant uptake (Nadeem et al., 2016). The consortium inoculation of *Bradyrhizobium* + *Pseudomonas* demonstrated that it boosted soil mineral N and P, thereby enhancing uptake of N and P and yield of mungbean (& Sani, 2024). This particular microbial strain, named "*P. aeruginosa* strain AGKT1" a rhizobacterium developed at Universiti Putra Malaysia as the active component of a patented biofertiliser formulation that may be applied in combination with NPK fertiliser (Raja Abd. Rahman et al., 2014). It is stated that this strain can be applied alone or in

consortium as a biofertiliser to reduce chemical fertiliser inputs through its characteristic nutrient-solubilising and plant growth-promoting mechanisms.

Pseudomonas mendocina/putida have been shown to facilitate more uptake of K, Ca, Mg, and Zn nutrients by wheat shoots and improve the K^+/Na^+ ratio and yield under salt stress (Dasila et al., 2023). *Pseudomonas spp. such as Pseudomonas fragi* EPS1 and *Pseudomonas aeruginosa* (ZSB-22) solubilise the complex form of zinc in soil (Kamran et al., 2017). In addition, *Fluorescent pseudomonads* mobilise Zn and K in Zn- and K-deficient soils, thereby increasing their concentrations in rice tissues and biomass (Ullah et al., 2022).

Reported results have proven that *Pseudomonas* spp. could fix N, solubilise P and K, produce siderophores, and mobilise micronutrients, thereby increasing macro- and micronutrient availability in the rhizosphere and supporting plant nutrition and soil health (Sah et al., 2021). While studies on microbial-based biofertilisers have been conducted on oil palm seedlings, most have used multi-strain consortia and assessed seedling growth or tissue nutrient content (Ajeng et al., 2020; Amir et al., 2005; Keni et al., 2023; Zainuddin et al., 2022). Consequently, the precise impact of an individual strain on the nutrient status of the nursery growing medium remained largely unknown. Furthermore, there is a gap in studies on whether the effect of a single *Pseudomonas* inoculant could sustain or exceed the nutrient availability achieved by full-dose NPK when chemical fertiliser is reduced by 50%, yet this has not been examined.

In light of the environmental concerns arising from the excessive usage of chemical fertiliser in the oil palm sector, this integrated approach offers a sustainable choice by improving soil biological and chemical properties while reducing ecological degradation. The synergy between microbial activity and reduced chemical inputs promotes balanced nutrient supply and supports soil microbial health. Consequently, the application of *P. aeruginosa* AGKT1-based biofertiliser, combined with reduced chemical fertiliser, offers a promising strategy for sustainable oil palm cultivation while strengthening soil ecosystem resilience. Therefore, this study aimed to evaluate the integrated application of biofertiliser and reduced chemical fertiliser as a strategy to enhance the microbial activity and soil-available nutrients in the potting mixture of oil palm seedlings.

MATERIALS AND METHODS

Experimental Design and Nursery Preparation

The experiment on Dura × Pisifera oil palm seedlings (RISDA, Malaysia) was established in a glasshouse at Universiti Putra Malaysia using a randomized complete block design with three replications. Seedlings were cultivated in 15 kg polybags (35 × 38 cm) containing a mixture of sieved topsoil, compost, and sand at a ratio of 3:2:1. Seedlings received NPK 15:15:15 fertiliser (18 g per plant) (Adileksana et al., 2020) and stage-dependent irrigation (50-120 mL). Soil N and P were determined via Kjeldahl digestion and molybdenum blue

Table 1
Treatment details

Treatment	Description	Reference
T0	No chemical fertiliser and no biofertiliser (Control)	
T1	Normal fertiliser (NPK Green, 15:15:15) (100% = 18 g)	Nusaibah et al., 2017
T2	25 mL Biofertiliser	Ajeng et al., 2020; Zainuddin et al., 2019
T3	50 mL Biofertiliser	”
T4	100 mL Biofertiliser	”
T5	T2 + 50% NPK Green (50% = 9 g)	”
T6	T3 + 50% NPK Green (50% = 9 g)	”
T7	T4 + 50% NPK Green (50% = 9 g)	”

colorimetry, respectively, while K, Mg, B, and Zn concentrations were quantified using ICP-AES. Treatments (Table 1) were administered over a four-month period. Chemical fertilisers were applied at 15-day intervals. The biofertiliser inoculum (10^6 CFU/mL) was applied at 14-day intervals for biofertiliser-only treatments (T2-T4), whereas combined treatments (T5-T7) received the inoculum one week following each chemical fertiliser application.

Determination of Soil Nutrients

Soil samples were air-dried, homogenised, and sieved through a 2 mm mesh before analysis. Macronutrients were assessed after four months to account for mineralisation and seasonal variation. Total nitrogen (N) was measured using the Kjeldahl method. Briefly, 1 g of soil was digested with concentrated sulfuric acid in the presence of a catalyst to convert organic N to ammonium sulfate. After the digestion, it was distilled with NaOH, and the liberated ammonia was trapped in boric acid and titrated with 0.01 N HCl (Okalebo et al., 1993). Total phosphorus (P) was determined using the molybdenum blue colorimetric method (Murphy & Riley, 1962), in which 0.5 g of soil was digested with concentrated H_2SO_4 and H_2O_2 at 350 °C temperature, allowed to react with molybdenum blue reagent, and absorbance was measured at 882 nm against phosphate standards using a spectrophotometer (Hansen & Koroleff, 1999). Available P was extracted using the double acid method (0.05 M HCl + 0.025 M H_2SO_4) (Sharpley, 2009), with 20 mL extractant shaken at 180 rpm for 10 minutes, then filtered using Whatman No. 2 filter paper, and P was determined colorimetrically at 882 nm following the same procedure for total P. Total Mg, Zn, and B concentrations were determined by aqua regia digestion (HCl: HNO_3, 3:1) (& Stein, 1983), whereby 2 g of soil was refluxed for 30 minutes, filtered into a 50 mL volumetric flask, and elemental concentrations quantified by Atomic Absorption Spectrometry (Perkin Elmer Analyst 400 AAS) and expressed as mg/kg.

Determination of Microbial Population in Soil

To assess the microbial population in soil, 1 g of soil from each treatment was collected after 45 days and serially diluted following standard microbiological procedures (Hernández-Fernández et al., 2021; Timmusk et al., 2017). The soil sample was initially mixed with 100 mL of distilled water, and a 10-fold serial dilution was performed up to 10^{-8}, using 1 mL aliquots transferred into 9 mL sterile distilled water (Naureen et al., 2015). Dilutions 10^{-4}, 10^{-6}, and 10^{-8} were plated on nutrient agar to determine colony-forming units (CFU) (Khan et al., 2018). For this study, the 10^{-6} dilution was selected to quantify the bacterial population and used in further analysis.

Statistical Analysis

Statistical analysis was performed using one-way ANOVA (SPSS v. 17.0), and mean comparison was done using the Least Significant Difference (LSD) test ($p < 0.05$).

RESULTS AND DISCUSSION

Effect of Biofertiliser on Microbial Population in the Potting Mixture of Oil Palm Seedlings

The presence of microorganisms in soil plays a critical role in enhancing micronutrient availability in crops through mechanisms such as siderophore production, secretion of organic acids, and release of phenolic compounds (Singh et al., 2021). The presence of endophytic bacteria, exemplified by *Pseudomonas* spp., showed the remarkable capacity to establish rhizo-competence, engage in antibiosis, induce resistance, and foster plant growth within the rhizosphere region (Nusaibah et al., 2017). However, in this experiment, soil microbial populations were monitored at four intervals using a dilution factor of 10^{-6}, and the results are presented in Table 2. The minimum values were seen in the T0 and T1 treatments at the end of the experiment, when a combination of NPK and a newly developed biofertiliser was employed, with recorded mean values of 8.25 CFU/mL and 8.50 CFU/mL, respectively. During the initial examination, the observed values ranged from 8.52 to 8.61 CFU/mL across all treatments. In the control group, the bacterial population at T0 exhibited linear growth, with a range of 8.11 to 8.91 CFU/mL.

However, treatment T1 also showed a comparable lower level of microbial population growth, indicating a difference between the applied biofertiliser and NPK fertiliser. In treatments T2 to T4, a relatively higher initial growth of the bacterial population was observed. However, upon conducting the subsequent analysis, a discernible increase in the proliferation of the bacterial population was noted. CFU values were found to be higher in treatments T5, T6 and T7 in comparison to treatments T0 and T1 (Figure 1), but they were found to be lower in treatments that used only biofertiliser and those without chemical fertiliser. Following the completion of the 45-day therapeutic regimen, an increase in the

Table 2
Microbial population growth of different treated soils over a span of four months with an interval of 45 days

Treatments	1st B.P.R*	1st log CFU/ mL	2nd B.P. R	2nd log CFU/mL	3rd B.P. R	3rd log CFU/mL	4th B.P. R	4th log CFU/mL
T0	13±1.00	8.11±0.03	15.66±1.52	8.11±0.03	16.33±2.51	8.20±0.06	18±2.64	8.25±0.06
T1	28±1.00	8.44±0.01	30.33±0.57	8.44±0.01	32.00±1.00	8.50±0.01	32±1.00	8.50±0.01
T2	34.66±1.52	8.53±0.01	51.33±4.93	8.53±0.01	56.33±5.85	8.74±0.04	64.33±1.52	8.80±0.01
T3	35.33±6.02	8.54±0.07	48.66±7.02	8.54±0.07	57.00±10.44	8.75±0.08	70±9.53	8.84±0.06
T4	41.66±1.52	8.61±0.01	60.66±8.38	8.61±0.01	68.00±8.71	8.82±0.05	81.66±1.52	8.91±0.01
T5	33.33±2.88	8.52±0.03	56.66±5.68	8.52±0.03	68.33±7.02	8.83±0.04	79.66±6.65	8.90±0.03
T6	37.66±2.30	8.57±0.02	48.00±9.64	8.57±0.02	54.33±6.11	8.73±0.04	68.66±3.05	8.83±0.01
T7	32.66±3.78	8.51±0.04	56.66±3.21	8.51±0.04	66.33±2.51	8.82±0.01	76±4.00	8.88±0.02

Note. *B.P. R= Bacteria production reading, T0 - No fertiliser, T1- Normal fertiliser (NPK Green), T2 - 25 mL Biofertiliser, T3 - 50 mL Biofertiliser, T4 - 100 mL Biofertiliser, T5 - T2 + 50% NPK Green, T6 - T3 + 50% NPK Green, T7 - T4 + 50% NPK Green)

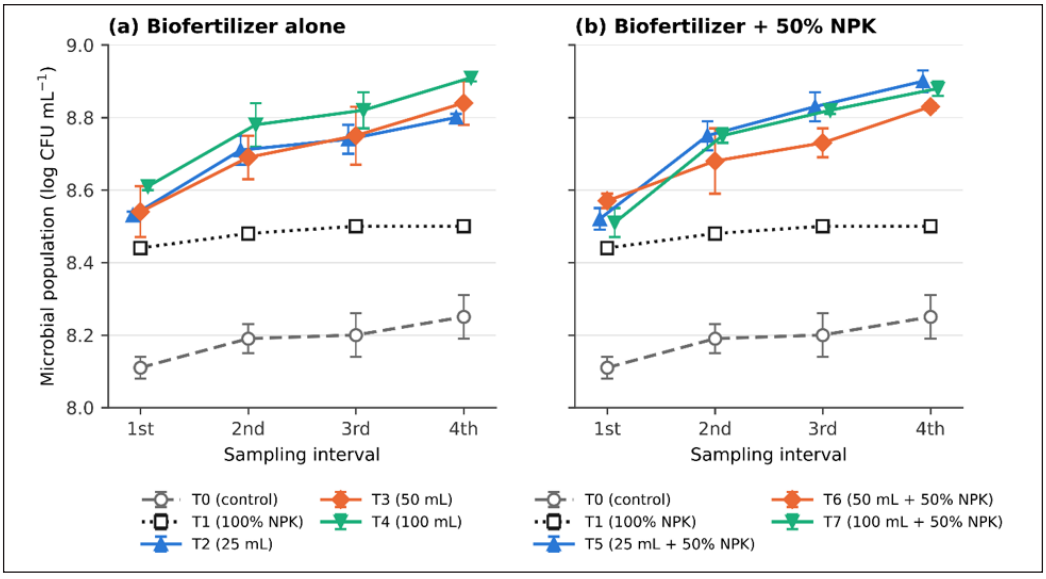


Figure 1. Microbial population growth in soil under various treatments over a four-month period, assessed at 45-day intervals: a) Biofertiliser alone, b) Biofertiliser + 50% NPK

proliferation of the bacterial population was observed in all treatments from T2 to T7. Following a 90-day treatment period, a subsequent decline in the growth of the bacterial population was observed. As an illustration of T2, the CFU value was 8.53 CFU/mL at 45 days, and the later measurement was 8.74 CFU/mL at 90 days, showing a decline in value as compared to the previous value. The growth rate decreased for most of the treatment, but it appears to have recovered after 135 days, when a significant increase was observed. This decline may be attributed to a multitude of factors, such as microbial adaptation, fluctuations in microbial nutrient availability, or alterations in the overall ecological equilibrium of the soil system over a given period. As previously mentioned, these soil microorganisms coexist within the rhizosphere, engaging in competitive interactions for nutrient acquisition, thereby setting up their rhizo-competence (Zboralski & Filion, 2020). Competition between microbial species can reduce microbial diversity in certain settings. Such competition for nutrients and niche space among indigenous and introduced microorganisms can temporarily suppress the population of an inoculated strain, as certain microbial taxa can dominate their habitats, analogous to weeds in plant communities (Cray et al., 2013).

In the final interval, T4 remained the most effective treatment, recording the highest B.P.R. (81.66) and log CFU/mL (8.91) (Table 2). T5 (79.66, 8.90) and T7 (76, 8.88) closely followed, showing strong microbial populations. T0, as expected, displayed the lowest values (18, 8.25). The superior performance of T4 and T5 suggests that these formulations optimised bacterial proliferation, likely due to improved nutrient availability and favorable rhizosphere conditions.

In the third interval, bacterial populations increased significantly across all treatments. T4 achieved the highest B.P.R. (68.00) and log CFU/mL (8.82), followed by T3 (57.00, 8.75) and T5 (68.33, 8.83). T0 continued to lag with the lowest B.P.R. (16.33) and log CFU/mL (8.20). These findings demonstrate that the biofertiliser formulations not only sustained microbial populations but also amplified them over time, especially in the 100 mL biofertiliser treatment. However, *Pseudomonas aeruginosa* GRC1*,* an isolate originating from the potato rhizosphere, showed remarkable rhizosphere competence and showed a stable presence within the rhizosphere ecosystem, while maintaining harmonious coexistence with the indigenous bacterial population (Pandey et al., 2005). In this context, we can hypothesise that the utilisation of our biofertiliser, treated with the modified *Pseudomonas aeruginosa* AGKT1 strain, may increase the competency within the rhizosphere, leading to a reduction, but later microbial proliferation increased within the treated soil.

In the first interval, the bacterial population ratio (B.P.R) and log CFU/mL values varied significantly among treatments. During the second interval, bacterial populations continued to expand, with T4 maintaining its position as the highest-performing treatment (B.P.R: 60.66; log CFU/mL: 8.61). T2 (51.33, 8.53) and T5 (56.66, 8.52) also exhibited strong bacterial proliferation. T0 again recorded the lowest values (15.66, 8.11). The consistent performance of T4 suggests its formulation supports stable microbial growth, due to its balanced nutrient composition and enhanced rhizosphere colonisation. Moreover, the microbial population in T6 and T7 revealed comparatively lower values (3rd and 4th readings) because of chemical fertiliser, which may negatively affect the microbial flora-fauna ecosystem in the soil (Backer et al., 2018; Basu et al., 2021; Singh et al., 2021).

In our experiment, after isolation of the microbe from the rhizosphere, it showed a green colour pigment, which is a sign of the presence of *Pseudomonas aeruginosa* AGKT1 (Pandey et al., 2005). The observed microbial presence confirms successful colonisation of the rhizosphere by the selected strain. Consistent with previous findings, such colonisation enhances soil nutrient availability through the secretion of organic acids that solubilise insoluble mineral fractions and the production of phosphatases and phytases that mineralise organic phosphorus. Additionally, the microorganism facilitates the mobilisation of potassium and zinc, with the magnitude of these effects influenced by soil aggregation and the presence of organic amendments (Muniroh et al., 2019; Rajawat et al., 2016; Sammauria et al., 2020).

Effect of Biofertiliser on Total N, P and Available P

Oil palm seedlings require an adequate level of macronutrients to achieve optimal growth and yield, which can be achieved through the application of biofertiliser (Keni et al., 2023). The presence of soil nutrients, including total N, P and available P**,** after the application

of newly formulated *Pseudomonas aeruginosa* AGKT1-based biofertiliser in oil palm seedlings are presented in Table 3. The highest mean total nitrogen content was observed in T4 (0.295%), which was statistically similar to T7 (0.263%) and T6 (0.233%).

Notably, T7 (100 mL biofertiliser + 50% NPK Green) and T6 (50 mL biofertiliser + 50% NPK Green) also recorded significantly higher nitrogen levels and statistically similar values to T4. In contrast, T0 (unfertilised control) and T2 (25 mL biofertiliser alone) recorded lower soil nitrogen contents and were not significantly different. The near-zero nitrogen content in T0 was expected given the complete absence of both chemical and biological nitrogen inputs. The comparably low nitrogen in T2 suggests that a sub-threshold biofertiliser dose of 25 mL was insufficient to establish adequate rhizospheric colonisation or sustain meaningful biological nitrogen fixation activity, particularly without supplementary NPK support.

The newly developed biofertiliser, with a 100 mL volume in T4, exhibited a moderate nitrogen content due to microbial nitrogen fixation. Whereas T1 (100% NPK Green alone) demonstrated lower nitrogen levels but exhibited the highest variability among replicates, reflecting the inconsistent distribution or retention of inorganic nitrogen from chemical fertilisers in the soil, which is susceptible to leaching and volatilisation losses (Zhu & Chen, 2002). Through secreting or solubilising insoluble complex compounds present in the soil, the application of biofertiliser can substitute for the availability of N and other macronutrients in soil. The mineral soil treated with biofertiliser exhibited a notable increase in nitrogen content when compared to soil treated with chemical fertiliser (Ajeng et al., 2020). Sufficient nitrogen facilitates the production of proteins, enzymes, and chlorophyll, hence enhancing the effective transformation of sunlight into energy via photosynthesis (Prasad et al., 2019).

Table 3
Total N, total and available P of different treatments in potting mixture

Treatments	Total Nitrogen %	Total P (mg/kg)	Available P (mg/kg)
T0	0.012±0.01 f	107.33± 3.05 e	10.66±1.16 f
T1	0.19±0.14 bdc	387.00 ± 5.56 a	19.90±2.08 e
T2	0.03±0.01 ef	244.66 ± 6.51 d	25.23±0.72 ed
T3	0.15±0.03 cd	266.33 ± 6.03 d	27.10±4.78 cd
T4	0.29±0.06 a	353.00 ±7.55 b	37.40±7.17 a
T5	0.12±0.01 ed	318.33 ± 6.51 c	32.433±4.76 abc
T6	0.23±0.02 abc	308.33 ± 16.07 c	29.10±0.53 bcd
T7	0.263±0.04 ab	327.66±30.66 c	34.86±3.70 ab

Note. T0 - No fertiliser, T1- Normal fertiliser (NPK Green), T2 - 25 mL Biofertiliser , T3 - 50 mL Biofertiliser , T4 - 100 mL Biofertiliser , T5 - T2 + 50% NPK Green, T6 - T3 + 50% NPK Green, T7 - T4 + 50% NPK Green

For total P, T1 recorded the highest concentration (387 mg/kg) in the potting mixture. It was resulted from the direct addition of inorganic phosphate-containing NPK fertiliser at full dose, which rapidly elevated total soil P through the incorporation of soluble phosphate salts. However, T4 had the second-highest total P (353 mg/kg), which was significantly higher than T5 (318 mg/kg), T7 (327 mg/kg), and T6 (308 mg/kg). These results indicate that the beneficial microorganisms, such as *Pseudomonas* spp. could accelerate the microbial processes through solubilisation to augment the extent of the nutrient's availability, such as phosphorus (Mahmud & Chong, 2021).

T0 (control, 107.33 ± 3.05 mg/kg) recorded the lowest total P, confirming the necessity of external nutrient inputs or microbial inoculation and that inherent soil phosphorus reserves in the growing medium were insufficient to sustain required phosphorus levels. Treatments combining lower NPK dosage with biofertiliser (T5, T6, T7) recorded intermediate total P values in the range of 308.33-327.66 mg/kg. High levels of total P are not necessarily transformed into equivalent plant-available P, as a substantial proportion of inorganic phosphate becomes immobilised through precipitation and adsorption reactions with soil minerals (Alori et al., 2017; Rodríguez & Fraga, 1999). Our experimental findings indicate that *P. aeruginosa* AGKT1 at the highest application rate effectively mobilised and increased total soil phosphorus, even in the absence of chemical fertiliser. Phosphate-solubilising *Pseudomonas* species convert unavailable inorganic phosphate to soluble forms by secreting organic acids including citric, oxalic, succinic, tartaric, and malic acids in the soil rhizosphere (Singh et al., 2021). Utilising a consortium of microbes in combination with synthetic fertiliser has been shown to effectively improve the overall and accessible phosphorus levels in soil (Keni et al., 2023).

Total P represents the overall phosphorus pool in the soil, while available P is the agronomically critical fraction directly accessible to plant roots for uptake. Results revealed a highly significant treatment effect on soil available P, with treatment means ranging from 10.66 mg/kg (T0) to 37.40 mg/kg (T4). T4 recorded the highest available P (37.40 mg/kg), significantly exceeding T0, T1, T2, and T3, and was statistically comparable only to T7 (34.86 mg/kg) and T5 (32.43 mg/kg). These results showed a considerable agronomic significance, as T4 achieved the highest plant-available P without any chemical fertiliser input, relying entirely on the phosphate-solubilising capacity of *P. aeruginosa* AGKT1. Critically, available P (37.40 mg/kg) in T4 substantially exceeded that of T1 (100% NPK, 19.90 mg/kg), despite T1 recording the highest total P overall. This divergence highlights a well-recognised limitation of inorganic phosphate fertilisers: their tendency to be rapidly fixed in the soil through precipitation with Ca, Fe, and Al ions, rendering a significant proportion of applied P unavailable for plant uptake (Alori et al., 2017; Kalayu, 2019). T7 (100 mL biofertiliser + 50% NPK, 34.86 mg/kg) and T5 (25 mL biofertiliser + 50% NPK, 32.433 mg/kg) also recorded elevated available P, which is statistically similar to T4. T0 (10.66 mg/kg) recorded the lowest available P, consistent with the absence of any

phosphorus input or phosphate-mobilising microbial activity. The release of these low-molecular-weight organic acids by P. *aeruginosa* AGKT1 likely dissolved mineral-bound phosphate complexes in the soil, elevating measurable total P concentrations (Sharma et al., 2013).

According to our study, T1 showed the highest Total P, whereas available P was dominated by T4, indicating that P. *aeruginosa* AGKT1 likely increased phosphorus abundance in the soil compared with chemical fertiliser alone. Phosphorus solubilisation via phosphate-solubilising bacteria provides a sustainable strategy to release unavailable or precipitated soil P in a plant-available form, with organic acid production being one of the key mechanisms by which *Pseudomonas* and related genera release bound phosphorus from mineral complexes (Kalayu, 2019).

Effect of Biofertiliser on Available B, Zn and Mg in Soil

The presence of micronutrients in the soil is crucial for the vigorous growth of oil palm seedlings. Micronutrients such as zinc, manganese, boron, iron, copper, and molybdenum are essential for carrying out important biochemical and physiological activities in oil palm plants (Woittiez et al., 2017). Boron is a critical micronutrient; its deficiency impairs root development, nitrogen absorption, and cell wall integrity, with over 90% of plant B residing in the cell wall, underscoring its structural and metabolic indispensability for establishing healthy root architecture (Srivastava et al., 2025).

Significant treatment differences were observed, with mean soil B concentrations ranging from 1.066 mg/kg (T0) to 3.51 mg/kg (T6). T6 (50 mL biofertiliser + 50% NPK Green, 3.51 mg/kg) recorded the highest soil boron concentration among T0, T1, T2, and T3. From Table 4, we can observe that, T5 (25 mL biofertiliser + 50% NPK Green, 3.07 mg/kg) and T7 (100 mL biofertiliser + 50% NPK Green, 3.06 mg/kg) recorded statistically similar B concentrations to T6. Further, results revealed that combined application of biofertiliser and chemical fertiliser produced comparably higher soil B levels. Previous studies suggested that application of biofertiliser increases the availability of boron, which is essential for the growth and development of plants (Zainuddin et al., 2022).

This trend clearly demonstrates that the combination of P. *aeruginosa* AGKT1 with reduced-dose NPK fertiliser consistently enhanced soil B availability more effectively than applied alone. T4 (100 mL biofertiliser alone, 2.84 mg/kg) recorded significantly higher B than T0, T1, T2, and T3, confirming that *P. aeruginosa* AGKT1 alone, without chemical fertiliser, contributed to soil B enrichment. In contrast, T0 (1.066 mg/kg) recorded the lowest soil B. Further, T1 (100% NPK Green, 1.876 mg/kg), T2 (25 ml biofertiliser, 1.85 mg/kg) and T3 (50 ml biofertiliser, 1.59 mg/kg) showed statistically similar B levels.

From Table 4, we can observe significant treatment differences, with mean soil Zn values ranging from 2.20 mg/kg (T6) to 4.18 mg/kg (T1). T1 (100% NPK Green, 4.18 mg/kg)

recorded the highest soil Zn content, which is statistically similar to T4 (100 mL biofertiliser alone, 3.84 mg/kg). The high soil Zn in T1 likely reflects the zinc content naturally present within the NPK Green (15:15:15) formulation or its carrier compounds. In contrast, T4 achieved comparably high soil Zn (3.84 mg/kg) without any NPK input, suggesting active zinc mobilisation by P. *aeruginosa* AGKT1 through biological mechanisms. T6 (2.20 mg/kg) recorded the lowest residual soil Zn. A previous experimental study suggests that P. *aeruginosa* effectively enhanced plant growth by solubilising zinc and phosphorus minerals present in the soil, with its Zn and P solubilisation ability facilitating the conversion of soil-unavailable mineral forms into plant-accessible forms (Sunitha Kumari et al., 2023). The mechanism involves secretion of siderophores and low-molecular-weight organic acids by *P. aeruginosa*, which chelate and dissolve mineral-bound zinc complexes, releasing Zn^{2+} ions into the rhizosphere solution (Krishnan Kutty et al., 2025). A close association between siderophore production capability and zinc solubilisation has been established in *Pseudomonas* strains, demonstrating that siderophore-producing PGPR significantly increase plant growth parameters including height, fresh weight, and dry weight in zinc-deficient soils (Gao et al., 2021).

Table 4
Availability of B, Zn, and Mg in many different types of treated potting mixture

Treatment Number	B (mg/kg)	Zn (mg/kg)	Mg (mg/kg)
T0	1.066±0.06 d	3.203±0.62 bc	19.63±2.31 c
T1	1.876±0.22 c	4.18±0.49 a	24.79±3.01 bc
T2	1.85±0.08 c	2.71±0.33 cd	33.98±2.34 ab
T3	1.59±0.20 c	2.73±0.34 cd	31.67±9.62 ab
T4	2.84±0.55 b	3.84±0.45 ab	35.14±9.97 ab
T5	3.07±0.14 ab	3.25±0.56 bc	26.41±4.70 bc
T6	3.51±0.31 a	2.20±0.26 d	33.32±3.97 ab
T7	3.06±0.16 ab	2.48±0.35 cd	40.55±8.60 a

Note. T0 - No fertiliser , T1- Normal fertiliser (NPK Green), T2 - 25 mL Biofertiliser , T3 - 50 mL Biofertilise, T4 - 100 mL Biofertiliser , T5 - T2 + 50% NPK Green, T6 - T3 + 50% NPK Green, T7 - T4 + 50% NPK Green

PGPR-based biofertilisers have been shown to enhance the availability of nutrients including nitrogen, phosphorus, potassium, sulphur, zinc, and iron through innovative biological strategies, with PGPR mobilising mineral nutrients that would otherwise remain locked in unavailable soil forms (Wang & Xu, 2026). Deficiency of Mg can hinder the production of chlorophyll and limit the effectiveness of photosynthesis, which ultimately results in a reduction in the overall development of the plant (Putra et al., 2016). In our experiment, the treatment results showed soil Mg values ranging from 19.63 mg/kg (T0) to 40.55 mg/kg (T7), representing more than a twofold increase between the lowest- and

highest-performing treatments. T7 (100 mL biofertiliser + 50% NPK Green, 40.55 mg/kg) recorded the highest soil Mg content and was assigned the highest statistical value, being significantly higher than T0, T1, and T5. Importantly, T7 did not differ significantly from T2 (33.98 mg/kg), T3 (31.67 mg/kg), T4 (35.14 mg/kg), and T6 (33.32 mg/kg), showing similar Mg levels. These results suggest that the integration of biofertilisers enhances the potential to optimise the performance of beneficial microorganisms while also improving the availability of magnesium in the soil (Sani et al., 2022; Yadav et al., 2021).

The superiority of T7 in soil Mg accumulation underscores the synergistic benefit of combining the maximum biofertiliser dose with reduced NPK application. T4 (100 mL biofertiliser alone, 35.14 mg/kg) and T2 (25 mL biofertiliser alone, 33.98 mg/kg) recorded elevated soil Mg levels comparable to T7, demonstrating that the biofertiliser component alone is capable of substantially increasing soil Mg availability across a range of application doses. In contrast, T0 (unfertilised control, 19.63 mg/kg) recorded the lowest soil Mg, confirming severely limited Mg availability in untreated soil. T1 (100% NPK, 24.79 mg/kg) and T5 (26.41 mg/kg) formed an intermediate grouping, both significantly lower than T7. Magnesium, as the central atom of the chlorophyll molecule and a cofactor for numerous phosphate-transferring enzymes, is indispensable for photosynthetic efficiency and carbohydrate metabolism in oil palm seedlings (Cakmak & Kirkby, 2008; Gransee & Führs, 2013). While Mg solubilisation is less extensively studied than P or Zn mobilisation by *Pseudomonas* spp., the organic acid production and mineral weathering activity of *P. aeruginosa* AGKT1 likely facilitated the release of Mg^{2+} ions from soil mineral complexes, particularly from magnesium silicates and carbonates prevalent in tropical soils (Sindhu et al., 2016). Additionally, the improvement in overall soil organic matter quality associated with PGPR rhizosphere activity enhances cation exchange capacity (CEC), which in turn promotes Mg^{2+} retention and availability in the soil profile (Bhattacharyya & Jha, 2012).

Most Effective Treatments

In our experimental study, T4 (100 mL biofertiliser alone, 8.91 log CFU/mL) recorded the highest soil microbial population, followed closely by T5 (25 mL biofertiliser + 50% NPK, 8.90 log CFU/mL). From Table 5, we can observe that the marginal difference between T4 and T5 indicates that a lower biofertiliser dose combined with reduced chemical fertiliser can sustain rhizospheric microbial populations comparable to those of the highest standalone biofertiliser application.

The dominance of T4 in soil N accumulation reflects the biological nitrogen fixation (BNF) activity of *P. aeruginosa* AGKT1 with highest microbial counts in T4 reflect the strong capacity of the nitrogenase enzyme complex responsible for converting atmospheric N_2 into plant-assimilable ammonium (NH_4^+) (Bhattacharyya & Jha, 2012; Shameer & Prasad, 2018). In terms of soil phosphorus, the proximity of T7 (2nd rank) to T4 suggests

Table 5
Summary of the best-performing treatments (1st and 2nd rank) across all measured soil parameters

Parameter	1st Best Value Treatment	2nd Best Value Treatment
Microbial population growth	T4= 8.91±0.01 CFU/ml	T5= 8.90±0.03 CFU/ml
Total Nitrogen %	T4= 0.29±0.06 %	T7= 0.263±0.04%
Total P (mg/kg)	T1= 387.00±5.56 mg/kg	T4= 353.00±7.55 mg/kg
Available P (mg/kg)	T4= 37.40±7.18 mg/kg	T7= 34.86±3.70 mg/kg
B (mg/kg)	T6= 3.51±0.31 mg/kg	T5= 3.07±0.14 mg/kg
Zn (mg/kg)	T1= 4.18±0.49 mg/kg	T4= 3.84±0.45 mg/kg
Mg (mg/kg)	T7= 40.55±8.60 mg/kg	T4= 35.14±9.97 mg/kg

Note. T0 - No fertiliser, T1- Normal fertiliser (NPK Green), T2 - 25 mL Biofertiliser, T3 - 50 mL Biofertiliser, T4 - 100 mL Biofertiliser, T5 - T2 + 50% NPK Green, T6 - T3 + 50% NPK Green, T7 - T4 + 50% NPK Green

that the combination of maximum biofertiliser dose with reduced NPK maintains competitive N levels in soil, supporting integrated nutrient management strategies. On the contrary, T1 (100% NPK Green, 387.00 ± 5.56 mg/kg) recorded the highest total soil phosphorus, with T4 (100 mL biofertiliser alone, 353.00 ± 7.549 mg/kg) ranking second. The highest total P in T1 is directly attributable to the large inorganic phosphate input from the full-dose NPK Green application, which immediately elevates the total soil P pool through the incorporation of soluble phosphate salts. In contrast, high total P in T4 was achieved entirely without chemical fertiliser and with the highest microbial presence in soil, attributable to the phosphate solubilisation activity of *P. aeruginosa* AGKT1, which produces organic acids including citric, gluconic, and oxalic acids that dissolve mineral-bound phosphate complexes (Singh et al., 2021). For available phosphorus, T4 (100 mL biofertiliser alone, 37.40 ± 7.175 mg/kg) recorded the highest, followed by T7 (100 mL biofertiliser + 50% NPK, 34.86 ± 3.70 mg/kg).

Despite exhibiting the highest population of *Pseudomonas aeruginosa* AGKT1 and elevated concentrations of major nutrients, including total nitrogen, total phosphorus, and available phosphorus, treatment T4 produced comparatively lower micronutrient accumulation except for Zinc. In our experimental study, the overall result shows a positive impact of implementing biofertiliser; a previous experiment also suggested that PGPR inoculation on oil palm seedlings under field nursery conditions has been demonstrated to significantly enhance nitrogen accumulation in plant tissues and improve total soil nitrogen status compared to unfertilised controls (Amir et al., 2005).

CONCLUSION

Among the analysed soil parameters, T4 (100 mL *Pseudomonas aeruginosa* AGKT1 biofertiliser alone) emerged as the most consistently superior treatment, ranking first in four parameters (microbial population growth, total N, available P, and Zn) and second in

two further parameters (total P and Mg). This treatment achieved these outcomes without any chemical fertiliser input, demonstrating the comprehensive capacity of P. *aeruginosa* AGKT1 to enhance soil nutrients under maximum standalone application. T7 (100 mL biofertiliser + 50% NPK) ranked first in Mg and second in both total N and available P, representing the most effective integrated biofertiliser-chemical fertiliser treatment. These findings reinforce the feasibility of integrating bio-based approaches into mainstream plantation management for more ecologically balanced and cost-effective agricultural practices. Based on this study, *Pseudomonas aeruginosa* AGKT1-based biofertiliser, applied at the highest dose (100 mL) alone or in combination with 50% NPK Green, consistently produced higher values for total soil N, available P, Zn, and Mg, highlighting the greater efficiency of biologically mediated nutrient solubilisation over inorganic fertiliser addition in enhancing plant accessibility. Future research should focus on field-scale validation and long-term effects of such formulations to support wide-scale adoption in sustainable oil palm production systems.

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Review Article

Herbicide Impacts on Weed Dynamics and Soil Microbial Communities in Rice Fields: Challenges and Opportunities for Sustainable Rice Production

Md. Ariful Islam Khalid[1,2], Md. Kamal Uddin[1]*, Mohd Firdaus Mohd Anuar[1], Ali Tan Kee Zuan[3], Muhammad Asyraf Md Hatta[4], Md. Parvez Anwar[5], and Suhel Mia[1,2]

[1]Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[2]Agronomy Division, Bangladesh Rice Research Institute, 1701 Gazipur, Bangladesh
[3]University-Driven Research Program – Regenerative Agriculture for Sustainable Crop Productivity, d/a Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[4]Department of Agriculture Technology, Faculty of Agriculture, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[5]Department of Agronomy, Bangladesh Agricultural University, 2202 Mymensingh, Bangladesh

ABSTRACT

Rice is an important staple crop, and its productivity can be severely affected by weed infestations, resulting in greater yield loss. In direct-seeded rice (DSR) systems, herbicides have been successfully used to control weeds, but issues with herbicide resistance and their effects on soil microorganisms persist. The purpose of the present study is to assess the effects of herbicides on rice ecosystems and to synthesise our knowledge of weed populations, soil microbial communities, and crop production. The results showed that herbicides are effective at suppressing major rice weeds, including *Echinochloa crus-galli, Cyperus difformis,* and *Monochoria vaginalis*, thereby reducing weed biomass and increasing rice yields. If used repeatedly or heavily, microbial abundances might be affected, and beneficial groups such as nitrogen-fixing bacteria and arbuscular mycorrhizal fungi (AMF) may be less active. These effects might threaten soil health and the sustainability of rice production. The review also emphasises the need to use integrated weed management (IWM) strategies that combine

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E-mail addresses:
Khalidbau95@gmail.com/ aikhalid.agro@brri.gov.bd (Md. Ariful Islam Khalid)
mkuddin@upm.edu.my (Md. Kamal Uddin)
m.firdaus@upm.edu.my (Mohd Firdaus Bin Mohd Anuar)
tkz@upm.edu.my (Ali Tan Kee Zuan)
m.asyraf@upm.edu.my (Muhammad Asyraf Bin Md Hatta)
parvezanwar@bau.edu.bd (Md. Parvez Anwar)
moynul.bau@gmail.com (Suhel Mia)
* Corresponding author

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herbicides with non-chemical methods and bioremediation to mitigate long-term ecological damage. Future studies should focus on optimising herbicide use and developing herbicide-resistant rice cultivars to improve rice production systems.

Keywords: Herbicide, rice, soil microbes, weed dynamics, yield

INTRODUCTION

Rice (*Oryza sativa* L.) is the second most produced cereal crop in the world, and over half of the world's population depends on it as a staple food (Zainuddin et al., 2021). For an estimated 3.5 billion people worldwide, rice is their main food source, particularly in Asia, where it contributes up to 50% of total dietary energy (Li et al., 2018). Beyond its role in food security, rice cultivation contributes greatly to rural livelihoods, economic development, and ecosystem stability (Meher et al., 2024). In order to meet future food demand, rice production is going to rise, especially in the upcoming decades, due to the world's population growth (Mohidem et al., 2022).

Despite its importance, rice productivity is severely constrained by several biotic factors, among which weed infestation is one of the most significant. Weeds compete with rice plants for light, nutrients, water, and space, potentially causing yield losses up to 50%-100% in direct-seeded rice (DSR) systems (Rodenburg et al., 2022). *Echinochloa* spp., *Cyperus* spp., *Leptochloa chinensis*, and *Oryza sativa f. spontanea* (weedy rice) are repeatedly identified as the most problematic due to their high competitiveness and adaptability to rice field conditions (Butts et al., 2022; Calha et al., 2022). Weeds exhibit strong adaptive capacity to different management practices, increasing the complexity of control strategies (Kumar, Choudhary, et al., 2022). In order to achieve the highest possible output in paddy fields, it is essential to take measures to control weed infestation (Ramli et al., 2024).

Herbicide use has been extensively proven as a successful strategy for reducing weed competition and enhancing crop performance (Olajumoke et al., 2016). Depending on when they are applied and how plants absorb them, herbicides can be broadly categorised into pre-emergence and post-emergence forms (Krähmer et al., 2021). In particular, post-emergence herbicides are extensively used in rice systems due to their ability to target weeds after they have emerged, thereby allowing more precise weed control (Sen et al., 2021).

However, the usage of herbicides to control weeds is increasing, which has raised several concerns related to their sustainability and long-term effectiveness (Wang et al., 2021). Inadequate application rates and the repeated use of the same herbicide can result in the development of herbicide-resistant weed populations, crop phytotoxicity, and reduced efficacy (Jin et al., 2022). In addition, excessive herbicide use can cause environmental

pollution and harm non-target organisms, such as beneficial soil microorganisms (Hakim et al., 2021).

Soil microbes are critical for soil health and plant growth. They cycle nutrients through the soil, clean up organic debris and treat diseases (Bhardwaj et al., 2024). Herbicide use can disrupt microbial populations and affect soil biochemical processes and the overall ecosystem (Xiong et al., 2021).

While recent reviews have examined sustainable weed management in rice (cultural, mechanical, biological, and chemical), there has been less focus on the ecology of weed control strategies that sustain crop production without long-term environmental impacts. Understanding these interactions is crucial for developing effective weed control methods that contribute to crop yields and minimise environmental impact. The review aims to provide an in-depth understanding of herbicide interactions in rice ecosystems, weed behaviour, resistance issues, impact on soil microbes and rice yields and sustainable recovery strategies.

METHODOLOGY

The review described the development and challenges in rice weed control, herbicide use, soil microbiology and crop biotechnology in recent years. The literature was searched through several major academic databases, e.g., Scopus, Web of Science, ScienceDirect and Google Scholar. The search terms were generated by incorporating keywords related to rice production, weed control, herbicide effectiveness, microbial interactions, soil ecology and biotechnological progress. Although older papers were also included for historical context, we mainly searched for recent papers published between 2019 and 2025. The retrieved articles were then analysed to determine their relevance for the purpose of the review.

HERBICIDE AND WEEDS IN RICE FIELD ECOSYSTEM

Impact of Herbicides on Weed Management

Post-emergence herbicides have proven highly effective at suppressing weeds in rice fields. Field trials in direct-seeded rice (DSR) systems have demonstrated that most post-emergence herbicides can reduce weed biomass by 60-90% within weeks of application (Jehangir et al., 2024). As shown in Figure 1, herbicide application interacts with various factors in the rice ecosystem, influencing both weed control and soil health. However, in DSR systems, the use of a single pre- or post-emergence herbicide often fails to control the broad spectrum of weeds present. As a result, tank mixtures or sequential applications of herbicides are commonly required (Kumar, Chhokar, et al., 2022).

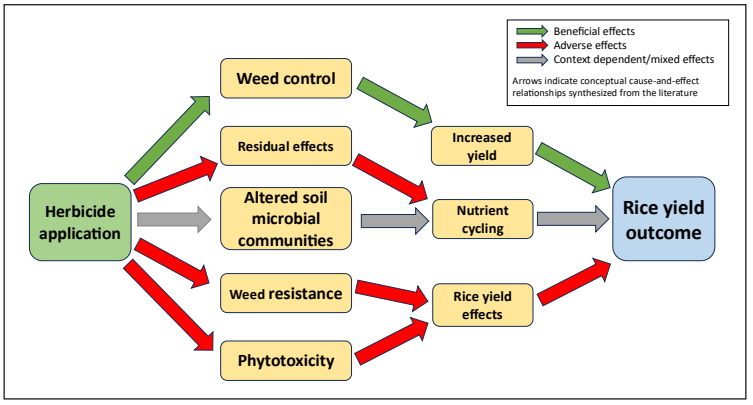


Figure 1. Herbicide effects on weed management, soil health, and rice yield

One innovative approach gaining traction in sustainable agriculture is Integrated Weed Management (IWM), which combines chemical and non-chemical control methods, including bioherbicides, to manage weed populations effectively (Kamala Bai et al., 2025). Given that rice fields in Asia host over 40 weed species (major weeds list shown in Table 1), selecting herbicides with diverse modes of action is essential for effective control (Chen et al., 2023). For example, Almix 20% WP has been shown to effectively control all types of weed populations in rice fields (Dey et al., 2020). While wet DSR faces challenges from diverse weed species, broad-spectrum herbicide mixtures can help mitigate issues such as weed shifts and herbicide resistance (Meher et al., 2024).

Table 1
Major weeds in rice fields in Asia (International Rice Research Institute [IRRI], 2025)

Weed Category	Scientific Name	Common Family Name
Grass	*Digitaria setigera*	Poaceae
	Digitaria ciliaris	Poaceae
	Echinochloa colona	Poaceae
	Echinochloa crus-galli	Poaceae
	Echinochloa glabrescens	Poaceae
	Eleusine indica	Poaceae
	Ischaemum rugosum	Poaceae
	Leptochloa chinensis	Poaceae
	Oryza sativa (weedy rice)	Poaceae
	Paspalum distichum	Poaceae
Sedge	*Cyperus iria*	Cyperaceae
	Cyperus difformis	Cyperaceae
	Cyperus rotundus	Cyperaceae
	Fimbristylis miliacea	Cyperaceae

Table 1 (*continued*)

Weed Category	Scientific Name	Common Family Name
Broadleaf	*Commelina benghalensis*	Commelinaceae
	Eclipta prostrata	Asteraceae
	Ipomoea aquatica	Convolvulaceae
	Ludwigia octovalvis	Onagraceae
	Ludwigia adscendens	Onagraceae
	Monochoria vaginalis	Pontederiaceae
	Sphenoclea zeylanica	Sphenocleaceae

The use of early post-emergence treatments, such as triafamone and ethoxysulfuron, has achieved 87-90% weed control efficacy while maintaining seed yields comparable to those in weed-free conditions, as demonstrated in two-year field trials (Jehangir et al., 2024). Additionally, Mathew et al. (2025) reported that the pre-emergence application of pretilachlor combined with pyrazosulfuron ethyl efficiently managed grasses, sedges, and broadleaf weeds, especially at 20 days after sowing (DAS). Furthermore, the application of Acetochlor, S-metolachlor, pyroxasulfone, dimethenamid-P, and pethoxamid, applied in fall, has been successful in controlling weedy rice in subsequent rice crops by more than 90% (Bertucci et al., 2019). Low doses of bispyribac sodium (20-40 g/ha) effectively controlled mixed weed flora, especially *Echinochloa* spp., *Cyperus difformis*, and *Monochoria vaginalis*, which lowered labour needs and weed management expenses (Ahmed et al., 2021).

Herbicide combinations, such as fenoxaprop-p ethyl 6.7% EC (w/w) + ethoxysulfuron 15% WDG (w/w) (50+15) g/ha, offer an effective solution for improved weed management and higher grain yield (Meher et al., 2024). However, some herbicide tank mixtures exhibit antagonistic interactions, as observed when quizalofop was mixed with other herbicides against various grass weed combinations (Lancaster et al., 2019). Herbicide tank mixtures can undergo three types of interactions: additive, synergistic, or antagonistic. Approximately 97% of farmers employ herbicide mixtures to reduce operational costs, labour hours, and machine entries (Barbieri et al., 2022).

Hakim et al. (2021) found that applying herbicides at higher than recommended doses, such as pretilachlor, propanil + thiobencarb, bensulfuron + MCPA, and pretilachlor, remains effective for both weed control and maintaining grain yield under salinity conditions. In addition to chemical control, non-chemical weed management tactics, such as hoeing at 12 DAS followed by Sesbania co-culture or rice straw mulching at 4-6 t ha^{-1}, demonstrated effective weed suppression in direct-seeded rice (Nagargade et al., 2024). Table 2 lists commonly used herbicides for weed control in rice cultivation.

Table 2
Herbicides commonly used in rice cultivation (Bakar, 2004; Mispan et al., 2019; Rajput et al., 2020)

S.N.	Common Name	Trade Name	Dose (g/ha)	Stages of Application / Salient Features
		Pre-Emergence Herbicide:		
1	Benthiocarb	Bolero	3400-4500	4-10 days after seeding (DAS). Flooding should be done 3-5 days after treatment.
2	Pendimethalin 30 EC	Stomp, Pendisar	1000-1500	0-3 DAS —annual grasses and some broadleaf weeds can be controlled.
3	Fluazfop_P	Fusilade	105-250	Applied before tillage at the 2-4-leaf stage of weedy rice.
4	Anilofos 30EC	Arozin, Anilogard	400	3-5 DAS —many annual grasses and some broadleaf weeds can be controlled.
5	Pretilachlor 30.7% EW	Sofit, Rift, Erage-N	550-700	0-3 DAS — for effective weed control, soil moisture must be wet for a few days.
		Post-Emergence and Mixture of Herbicides:		
1	Fenoxaprop-p-ethyl 6.7EC	Rice Star	57-61	25-30 DAS —Should be applied with all pre-emergence herbicides. Excellent control of annual grasses.
2	Bispyribac-sodium 10SC	Nominee Gold, Adora	20	15-20 DAS — Controls annual grasses, some broadleaf weeds and sedges.
3	Propanil	Stam, Tawan	2000-4000	Controls weeds and annual grass; has low soil persistence.
4	Chlorimuron-ethyl + Metsulfuron-methyl 20 WP	Almix	4	15-20 DAS —annual broadleaf weeds and grasses can be controlled
	Quinclorac	Qunstar, Rumpas M	250	Superior control of barnyard grass.
5	Molinate + Bensulfuron	Londax	3.0 + 0.03 kg a.i./ha	6-10 DAS — Wide spectrum of weed control under standing water conditions.
6	Bispyribac-sodium 10SC + Almix	Adora + Almix	20 g + 4 g a.i./ha	20 DAS — Kills all types of weeds.
7	Pretilachlor 30.7% EW + Bispyribac-sodium 10SC	Nominee Gold + Sofit	600 + 20	1-3 and 20 DAS — Pre- and post-emergence herbicides, which give the best results.

Integrated weed management (IWM) strategies that combine crop rotation, herbicide rotation with different modes of action, proper timing, and economic combinations help to disrupt weed life cycles and provide effective management (Kaur et al., 2023). In addition, the development of herbicide-resistant rice types through CRISPR-Cas-mediated gene editing and genomic transformation has been identified as a promising approach to managing weed populations (Luo & Liu, 2025).

Herbicide Resistance Development in Weeds

Rice productivity, despite its global importance, is severely constrained by weed pressure, widely recognised as a major biotic stress (Rahaman et al., 2021). The heavy reliance on herbicides has led to the emergence of herbicide-resistant weed populations, which in turn reduce rice yields and increase production costs (Onwona-Kwakye et al., 2020). Herbicide resistance has been reported in 37 distinct cases, involving 30 active herbicide components and 17 different weed species (Casimero et al., 2022). Resistance to commonly used herbicides, such as quinclorac, penoxsulam, and metamifop, has become increasingly prevalent (Wang et al., 2021). Barnyard grass, a major weed species, has also developed resistance to propanil (photosystem-II inhibitor), with 85 of 116 resistance cases reported between 1986 and 2022 (Damalas & Koutroubas, 2023).

Integrated herbicide resistance management strategies, such as crop rotation, herbicide rotation with different modes of action, the use of residual herbicides, proper timing of applications, and combining chemical control, are essential for managing this growing problem (Kumar et al., 2023). Advances in genetic modification, such as CRISPR-Cas9, have enabled the development of herbicide-resistant rice varieties. For example, a study demonstrated the creation of herbicide-tolerant Basmati rice using homology-directed repair of the OsALS gene, conferring resistance to bispyribac-sodium and chlorsulfuron while maintaining normal plant phenotype and yield (Zafar et al., 2020).

Development of Herbicide-Tolerant Rice

In rice fields, most herbicides that control weeds often harm the rice crop itself. Therefore, herbicide-resistant rice varieties are being developed to alleviate the weed problem (Jin et al., 2022). Transgenic techniques have been used to produce glyphosate- and glufosinate-resistant rice, although their safety remains a limiting factor for commercial use (Luo & Liu, 2025). Additionally, CRISPR/Cas9 technology has shown promise in modifying rice endogenous genes to create herbicide-resistant rice (Liu et al., 2020). Figure 2 shows the techniques involved in developing herbicide-resistant rice.

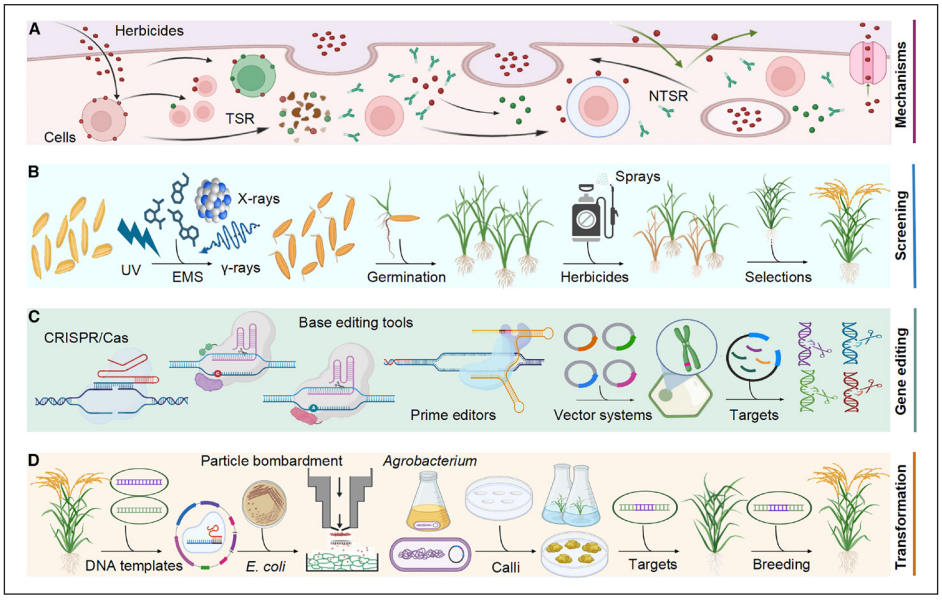


Figure 2. Graphical illustrations of the techniques applied in developing herbicide-resistant rice (Luo & Liu, 2025); (A) Rice cells resist herbicides through two main mechanisms: target-site resistance (TSR; conferred by mutations or overexpression of target proteins) and non-target-site resistance (NTSR; involving herbicide sequestration, detoxification, translocation via metabolic degradation, or reduced penetration); (B) Screening herbicide-resistant rice mutants created by chemical or irradiation, followed by herbicide treatment provides selection pressure; (C) Herbicide-resistant rice breeding using gene knockout, base editing, and prime editing; (D) Particle bombardment and Agrobacterium-mediated transgene transfer are the main herbicide-resistant rice breeding technologies

HERBICIDE AND SOIL MICROORGANISM

Impact of Herbicides on Soil Microbes

The growing global population and demand for food have increased herbicide use, raising environmental concerns and harming beneficial soil microorganisms (Shultana et al., 2025). The application of herbicides can greatly alter soil microbial communities, frequently resulting in a decrease in microbial abundance within 7 to 30 days post-treatment (Kremer & Means, 2009). The intensity of these impacts varies with soil attributes, including texture, tillage practices, organic matter content, and the chemical properties of the herbicides used (Yadav et al., 2017).

Studies on herbicides provided more insight into how they affect soil microorganisms. For instance, applying bispyribac sodium led to a considerable decrease in soil enzyme activity and microbial biomass carbon (MBC), even at the recommended dose (35 g/ha) and double dose (70 g/ha) (Kumar et al., 2020). On the other hand, it was found that the more recent herbicide tripyrasulfone, which contains an HPPD inhibitor, only temporarily affected soil enzyme activity in rice fields and posed no long-term risk to the soil's overall health (Sun et al., 2024).

Mixtures of herbicides such as atrazine, nicosulfuron and mesotrione have been shown to alter the composition of soil microbial communities. These mixtures tend to favor the increase of herbicide-tolerant taxa and the suppression of herbicide-sensitive species (Ma et al., 2025). In some cases, strategies combining herbicide use and water management (e.g. preventing seed dispersal by water) have been found to contribute to the conservation of beneficial microorganisms, including AMF (Li et al., 2025).

Inorganic pesticides and herbicides can affect AMF, which are important for plant nutrient uptake, in both positive and negative ways. These fungi absorb active chemicals from the rhizosphere either through plant roots or fungal hyphae (Hage-Ahmed et al., 2019). Herbicide mixtures can greatly reduce the abundance of beneficial microbes, such as *Bacillus,* but enrich for other species, such as *Penicillium*, as shown in research (Ma et al., 2025). Also, some herbicides, such as fomesafen, have been shown to affect the microbial interactions in the rhizospheres of legumes, greatly reducing the activity of the nifH gene, which is known to be related to nitrogen fixation (Chen et al., 2025).

In direct wet-seeded (DWS) rice systems, herbicide application initially reduces the populations of soil bacteria, fungi, and actinomycetes. Still, these microbes can bounce back 55 days after sowing, and therefore, herbicide toxicity diminishes over time (Mathew et al., 2023). This ability to degrade herbicides means that microorganisms can also serve as bioindicators of soil health, offering insights into changes within the soil ecosystem after herbicide application (Milošević & Govedarica, 2002).

A notable concern is that glyphosate-based herbicides significantly decrease AMF spore and vesicle biomass, as well as overall mycorrhizal colonisation of roots (Zaller et al., 2014). Despite these negative effects, bioremediation has been proposed as a potential solution to address herbicide residues in soil. This microbial approach can aid in herbicide degradation, although its effectiveness may be limited by the risk of producing toxic metabolites during the degradation process (Pileggi et al., 2020). Figure 3 shows the soil environment as a container, showing where each type of microbe lives, how herbicides affect them, and where bioremediation steps in.

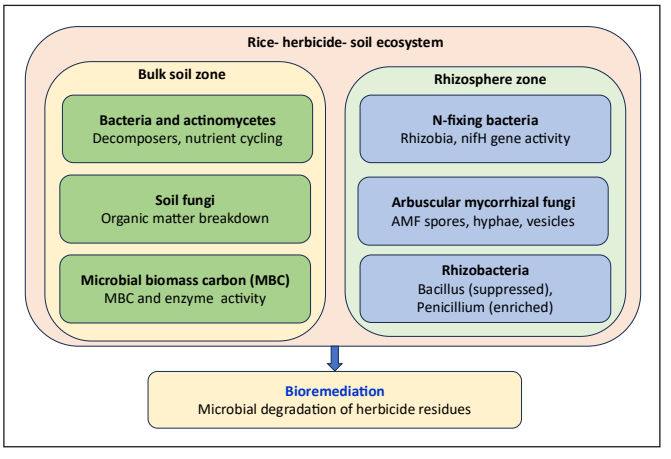


Figure 3. Herbicide impacts on soil microbial communities and bioremediation. Arrows represent conceptual cause-and-effect relationships and interactions synthesised from existing literature

HERBICIDE AND RICE YIELD

Weed competition can remarkably reduce rice yields, with potential losses reaching up to 80% in the absence of effective weed management strategies (Kraus & Stout, 2019). Pre-emergence herbicides have been shown to increase grain yields by 16-15% across consecutive cropping seasons, particularly when combined with high fertiliser rates, optimal seed drills (80 kg ha^{-1}), and improved canopy growth uniformly in direct-seeded rice systems (Liao et al., 2021). However, not all herbicides are equally effective. Research shows that pendimethalin at 2 kg ha^{-1} reduced rice plant SPAD values (a measure of chlorophyll content) by 100%, leading to severe phytotoxicity. In contrast, pretilachlor with safener showed minimal phytotoxicity and did not affect rice biomass (Motmainna et al., 2025).

Certain herbicides have demonstrated substantial yield improvements. For example, applying Almix 20% WP at 4g a.i. ha^{-1} increased rice yields around 59.1% compared to the untreated control (Dey et al., 2020). Herbicide mixtures such as Pretilachlor followed by Bentazon/MCPA, or Bispyribac-sodium followed by Bentazon/MCPA, showed enhanced weed control efficacy and increased rice grain yields, resulting in better economic returns (Abdullah et al., 2023). Interestingly, hand weeding also proved highly effective, with a yield of 5.50 t ha^{-1}, comparable to the combination of bensulfuron-methyl + pretilachlor (5.39 t ha^{-1}) and triafamone + ethoxysulfuron (5.29 t ha^{-1}) (Nagarjun et al., 2025).

Some herbicide combinations are more suited for specific growth stages. For example, Pretilachlor + pyrazosulfuron ethyl was most effective for early weed control, while pendimethalin followed by triafamone + ethoxysulfuron was ideal for managing late-season weed pressure and maximising rice yields (Mathew et al., 2025). Another study shows that the application of imidazoline herbicide 28 days before planting can result in a 10 % reduction in plant height or grain production in non-tolerant rice (Chiapinotto et al., 2024). Additionally, a study revealed that mechanised conoweedings coupled with the pre-emergence application of bensulfuron methyl + pretilachlor (60 and 600 g a.i. ha^{-1}) and post-emergence treatment with 2,4-D (0.75 kg a.i. ha^{-1}) resulted in improved crop growth and enhanced yields (Mir et al., 2024). In trials, the pre-mix triafamone + ethoxysulfuron proved most effective against grasses and sedges, achieving a remarkable 383% increase in yield, reaching 7.3 t ha^{-1} compared to the weedy check (Jehangir et al., 2024). The conceptual framework summarising the interactions of herbicides and rice yield is presented in Figure 4.

Herbicides like oxadiazon also demonstrated substantial benefits, boosting rice grain yield by 61% (4.6 t/ha) compared with untreated controls. This highlights the importance of selecting herbicides based on soil moisture regimes to optimise yield (Onwuchekwa-Henry et al., 2023).

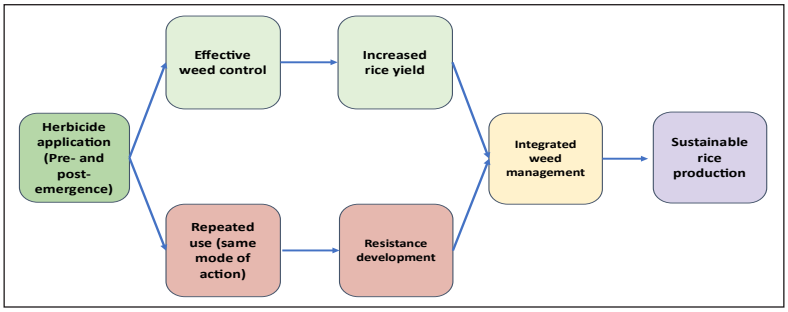


Figure 4. Herbicide effects on weed management and rice sustainability. Arrows indicate conceptual cause-and-effect relationships synthesised from the literature

RESIDUAL EFFECT OF HERBICIDE

Herbicides can increase crop yields but may also cause long-term issues if overapplied in soil, leading to phytotoxicity and herbicide residues that can contaminate groundwater and pose food safety risks (Sondhia & Singh, 2018). Herbicides may remain in the soil longer with different application methods. Banded applications that target smaller areas use less herbicide and thus are less likely to be associated with residual effects than broadcast applications (Curran, 2016).

In water-seeded rice, pendimethalin application after emergence (as a byproduct of or in combination with other herbicides) can provide residual soil activity to control late-emerging grasses (Becerra-Alvarez & Al-Khatib, 2025). Bommayasamy and Chinnamuthu (2024) also found that the residual effects of oxadiargyl-loaded zeolite from rice cultivation have been beneficial in reducing weeds and increasing crop growth, yield, and nutritional quality in the following crops, such as okra.

Heavy rainfall or irrigation can induce herbicide runoff, whereas high temperatures exacerbate the breakdown of herbicide residues through chemical and microbiological processes (Norsworthy et al., 2024). Fomesafen has been widely used in legume crop soils, leading to high residue buildup in the rhizosphere and, therefore, negatively impacting nitrogen-fixing microbial communities in the soil (Chen et al., 2025).

Soil microbes are affected by residual herbicides when residues exceed 310 µg/kg, compared with soils with lower residuals (Wang et al., 2024). Residual herbicides may influence the processes of soil ecology, for example, sulfur oxidation and phosphorus absorption, which are essential to soil health and plant growth (Cao et al., 2023). Herbicide residues may even encourage microbes to break them down, forming an ecological community, and thus microbes may adapt to these residues (Ruuskanen et al., 2023).

Low residual herbicide levels can increase the relative abundance of microorganisms that benefit soil processes, thereby increasing soil multifunctionality (Gao et al., 2024). Herbicides like atrazine and acetochlor significantly decrease the presence of essential

microbial groups such as actinobacteria, proteobacteria and acidobacteria, which play a fundamental role in nutrient cycling (Zhang et al., 2023).

The chemical properties of a herbicide, its environmental conditions in soil, and its half-life are factors that affect its persistence, especially for soil applications. Table 3 shows the half-lives of some common herbicides in soil that farmers and agronomists need to understand to manage residual impacts.

Table 3
Some herbicides half-lives in soil (Sondhia, 2016)

Herbicide	Half-Life (Days)	Toxicity Class Based on LD50
2,4-D	7-22	II-III
Chlorsulfuron	31-93	IV
Chlorimuron	60	IV
Fluazifop-p-butyl	8-24	III
Fluchloralin	12-46	IV
Atrazine	13-58	III
Butachlor	5-24	III
Flufenacet	9-22	V
Metribuzin	23-49	III
Metolachlor	8-27	IV
Sulfosulfuron	3-27	IV
Dithiopyr	11-25	IV
Imazethapyr	57-71	IV
Isoproturon	13-21	III
Metsulfuron-methyl	70-147	IV
Thiobencarb	19-24	III
Pyrazosulfuron-ethyl	16-21	IV
Oxyfluorfen	12-29	III
Pendimethalin	15-77	IV
Pretilachlor	10-11	IV

RECOVERY STRATEGIES FOR HERBICIDE EFFECTS AND SUSTAINABLE AGRICULTURE

The demand for chemical herbicides is steadily increasing due to their proven effectiveness in controlling weed growth and maximising crop productivity (Al-Samarai et al., 2018). However, herbicide persistence in agricultural environments can cause long-term ecological and soil health issues, making herbicide removal solutions essential for sustainable agriculture (Hassaan & El Nemr, 2020). The effects of herbicide application on weed control, crop yield, and soil biological properties reported in previous studies are summarised in Table 4.

Table 4
Herbicide effects on weed control efficiency, crop yield, and soil microbial responses

Herbicide Treatment & Dose	Weed Control Efficacy	Yield Response	Soil Microbial & Enzyme Response	Study Location	References
Almix 20% WP (Chlorimuron-ethyl + Metsulfuron-methyl) @ 4 g a.i./ha	Effective broad-spectrum weed suppression	59.1% yield increase compared to the untreated control	Minor temporary residue effect on soil microbes	India	Dey et al. (2020)
Bensulfuron-methyl + Pretilachlor OR Triafamone + Ethoxysulfuron	High weed control efficacy	Yields of 5.39 t/ha & 5.29 t/ha, comparable to Hand Weeding (5.50 t/ha)	Minimal effects on soil microflora and nutrient dynamics	India	Nagarjun et al. (2025)
Bispyribac-sodium (post-emergence) @ recommended (35 g/ha) & double (70 g/ha) dose	High post-emergence control of grass, sedge, and broadleaf weeds	Not measured	decrease in soil enzyme activities and MBC	India	Kumar et al. (2020)
Sequential Pre- and Post-emergence herbicide applications	Continuous weed suppression throughout the vegetative phase	High compatibility with crop yield potential	Initial population suppression of bacteria, fungi, and actinomycetes; recovery by 55 DAS	India	Mathew et al. (2023)
Triafamone + Ethoxysulfuron (early post-emergence)	87.0% - 90.0% control; 60.0% - 90.0% biomass reduction	383.0% yield increase (7.3 t/ha) vs. untreated check	Not explicitly evaluated	India	Jehangir et al. (2024)
Tripyrasulfone (QYR301, HPPD-inhibitor post-emergence)	High selective control	Safe for rice crop; preserves yield potential	Rapid soil dissipation (half-life 4.3-8.0 d); temporarily stimulates urease/phosphatase	China	Wang et al. (2019)
Oxadiazon (pre-emergence)	High pre-emergence control depending on soil moisture	61.0% yield increase (4.6 t/ha) compared to the untreated control	Not measured	Cambodia	Onwuchekwa-Henry et al. (2023)
Fomesafen (post-emergence residues)	General broadleaf control	Not measured	Negatively impacts nitrogen-fixing communities; heavily reduces nifH abundance	China	Chen et al. (2025)

The studies presented in Table 4 show that the use of herbicides typically results in better weed control and higher crop yields. Although some compounds have only a small impact on soil microbial characteristics, others might temporarily reduce microbial numbers or alter specific functional microbial communities. Therefore, recovery strategies should focus not only on herbicide removal but also on restoring soil biological functions.

Among the available approaches, microbial-based remediation and nanotechnology-assisted degradation have gained attention for their potential to reduce herbicide residues and restore soil health. Herbicide degradation may be enhanced by TiO_2 and ZnO nanomaterials. These nanomaterials protect microbial degraders and promote microbe-herbicide interactions (Sunanda & Ghosh Sachan, 2023). Pseudomonas and Acinetobacter strains can degrade hydrocarbons at 72-96%. These bacteria are also resistant to 2,4-D, imazethapyr, and tribenuron-methyl, making them promising bioremediation candidates for soil herbicide pollution (Korshunova et al., 2024). Apart from microbial-based methods, plant-derived chemicals have emerged as potential long-term alternatives to synthetic herbicides.

Allelochemicals produced by allelopathic plants are a more environmentally friendly weed management method. This is something that could be used for the greenhouse effect (Rahaman et al., 2022). And herbicides developed from natural compounds are relatively cheaper and more eco-friendly than manufactured ones (Bashar et al., 2023). Plant-based alternatives, such as Nerium and Olive extracts, are also promising for weed control, as well as to meet the increasing demand for sustainable agriculture and herbicide-free agriculture, while keeping herbicide use low (Al-Samarai et al., 2018). These solutions will prevent the use of herbicides and help address the mounting demand for sustainable farming practices.

In metabolic modelling (Figure 5), further developments contribute to the development of more efficient recovery strategies. By simulating the metabolic capabilities of microbial herbicide degraders, researchers can design more effective bioremediation methods that target herbicide toxicity. This approach enhances the ability to reduce herbicide residues in soil, fostering long-term agricultural sustainability (Dhakar et al., 2022).

Climate change may affect herbicide persistence, degradation, and efficacy by altering temperature, precipitation, soil moisture, and microbial activity. Therefore, future herbicide management strategies should incorporate climate-adaptive approaches to ensure effective and sustainable weed control (Zhang et al., 2023).

In addition to biological and technological approaches, regulatory frameworks are crucial to promoting sustainable herbicide management. Regulatory agencies, such as the United States Environmental Protection Agency (EPA), assess herbicides for environmental fate, toxicity, and ecological risks before approval and may impose restrictions on their use to minimise adverse impacts (U.S. Environmental Protection Agency, 2024). Similarly, the European Union Regulation (EC) No. 1107/2009 and the Sustainable Use of Pesticides

Directive 2009/128/EC emphasise precautionary assessment, reduced pesticide dependence, and the adoption of integrated pest management practices (European Parliament and Council of the European Union, 2009). Therefore, integrating recovery strategies, climate-adaptive approaches, and regulatory policies is essential to achieving long-term sustainability in rice production systems.

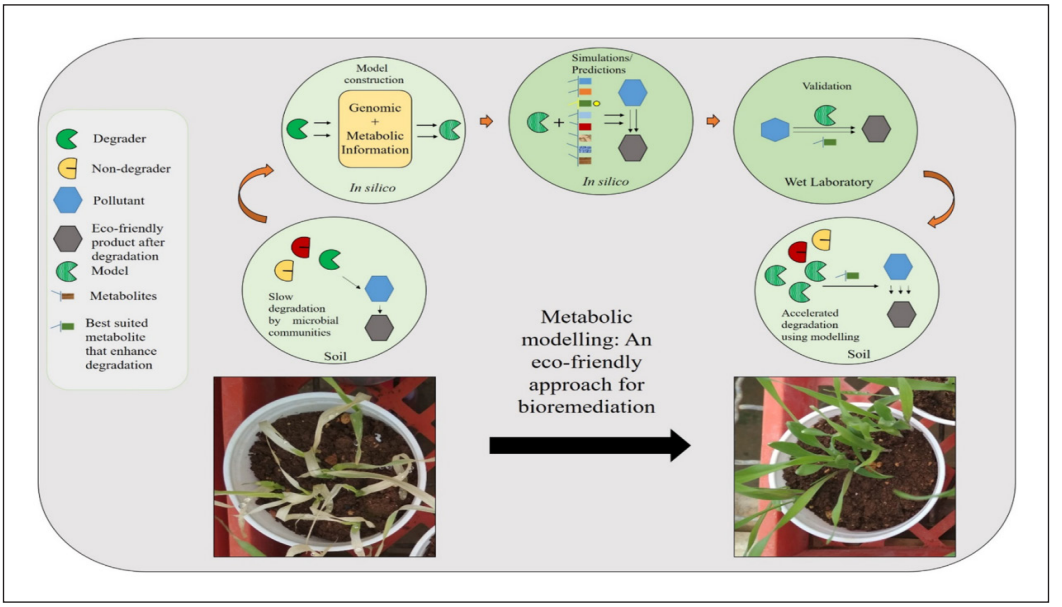


Figure 5. An overview of the various stages involved in the metabolic modelling approach for bioremediation (Dhakar et al., 2022)

CONCLUSION

Several studies have shown that herbicides can reduce the abundance of micro-organisms, harm nitrogen-fixing bacteria, prevent AMF from colonising the soil, and disrupt soil enzyme activity. Although herbicides are effective at weed control, with an efficacy rate of 85 to 95 percent, which results in higher crop yields, they also cause considerable problems. As the half-lives of herbicides range from a few days to several months, there are concerns about their residual effects on delicate crops and on soil biological activity. Dependence on herbicides can be reduced by using bioremediation, organic amendments, and precise application methods. The development of herbicide-resistant rice varieties through advanced breeding represents a promising strategy for selectively controlling weeds. Future research should focus on long-term ecological monitoring, soil health indicators, herbicide-resistant rice, and the use of low-risk herbicides. These measures will make herbicide use more efficient, thereby contributing to more sustainable farming practices.

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Review Article

Trichoderma spp. for the Sustainable Management of Northern Corn Leaf Blight: Biology, Mechanisms of Action, Practical Applications and Future Perspectives

Rabiul Islam[1], Khairulmazmi Ahmad[1]*, Fariz Adzmi[2], Nursyafiqi Zainuddin[1], Md. Shahin Alam[1], Khondoker Mohammad Alam[1], S.M. Kamrul Hasan Chowdhury[1], Annika Jahan Aonti[3], and Akbar Hossain[3]

[1]*Department of Plant Protection, Faculty of Agriculture, Universiti Putra Malaysia, 43400 Serdang, Selangor Darul Ehsan, Malaysia*

[2]*Laboratory of Processing and Product Development, Institute of Plantation Studies, Universiti Putra Malaysia, 43400 Serdang, Malaysia*

[3]*Soil Science Division, Bangladesh Wheat and Maize Research Institute, 5200 Dinajpur, Bangladesh*

ABSTRACT

Exserohilum turcicum, the causal agent of northern corn leaf blight (NCLB), is one of the most destructive foliar pathogens of corn, causing significant yield losses and threatening global corn production. The increasing demand for sustainable disease management has stimulated interest in using *Trichoderma* spp. as biological control agents in integrated disease management (IDM) programmes. This review synthesises current knowledge on the potential of *Trichoderma* spp. for managing NCLB, with emphasis on their biology, mechanisms of action, practical application and future perspectives. Studies consistently demonstrated that *Trichoderma* spp., particularly *T. asperellum*, *T. harzianum*, and *T. virens*, effectively suppress *E. turcicum* under *in vitro*, greenhouse, and field conditions. Their biocontrol efficacy is attributed to multiple complementary mechanisms, including mycoparasitism, production of antifungal metabolites and cell wall-degrading enzymes, competition for nutrients and ecological niches, and activation of induced systemic resistance (ISR) in the host plant. The review also examines the integration of *Trichoderma* with fungicides and cultural practices, highlighting their compatibility and potential for synergistic effects. Furthermore, available formulation and delivery methods, including seed treatments, soil applications,

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E-mail addresses:
gs72943@student.upm.edu.my (Rabiul Islam)
khairulmazmi@upm.edu.my (Khairulmazmi Ahmad)
farizadzmi@upm.edu.my (Fariz Adzmi)
nursyafiqi@upm.edu.my (Nursyafiqi Bin Zainuddin)
gs73157@student.upm.edu.my (Md. Shahin Alam)
gs70891@student.upm.edu.my (Khondoker Mohammad Alam)
gs70615@student.upm.edu.my (S.M. Kamrul Hasan Chowdhury)
tanjimar2003@yahoo.com (Akbar Hossain)
aonti@bwmri.gov.bd (Annika Jahan Aonti)
* Corresponding author

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seedling inoculation, and foliar sprays, are discussed with respect to their effectiveness under different production systems. Finally, key challenges, including inconsistent field performance, environmental influences, formulation stability, commercialisation constraints, and regulatory considerations, are critically evaluated. Addressing these knowledge gaps through multidisciplinary research will facilitate the wider adoption of *Trichoderma*-based biocontrol strategies as sustainable components of IDM programmes to effectively manage northern corn leaf blight.

Keywords: Antagonism, antibiosis, biological control, *Exserohilum turcicum,* northern corn leaf blight, *Trichoderma*

INTRODUCTION

Corn (*Zea mays* L.) is one of the most important cereal crops and a key member of the Poaceae family. It is a staple food for millions of people and the raw material for livestock feed and many industrial products such as starch, glucose, ethanol, cooking oil, paper, cosmetics, and pharmaceuticals (Reddy, 2008). Corn is economically and nutritionally important, and stable corn productivity is needed for sustainable global food security.

Despite ongoing improvements in crop production, corn is still plagued by several diseases that reduce yield and grain quality. Northern corn leaf blight (NCLB), also known as *Turcicum* leaf blight, is one of the most damaging foliar diseases in corn production, especially in warm and humid areas of the world (Ijaz & Fan, 2024). The disease is caused by *Exserohilum turcicum* (syn. *Setosphaeria turcica*) and may result in yield loss ranging from 15-66%, depending on the cultivar, the environment, and the stage of crop development at infection (Manu et al., 2018). NCLB is characterised by long elliptical, greyish-green to tan necrotic lesions on the leaves and progressively decreases the area around the photosynthetic plant cells. Infection during the tasselling and grain-filling stages can significantly reduce kernel production and grain yield, especially during prolonged periods of high humidity and moderate temperatures, which support pathogen growth.

Chemical fungicides remain an important and commonly used approach to managing NCLB because they are fast and effective at disease control and easily available to growers. However, repeated fungicide use increases the cost of production and has environmental implications for fungicide residues and the development of fungicide-resistant pathogen populations. These challenges have motivated the search for sustainable and environmentally friendly solutions for integrated disease management (IDM) programmes.

Trichoderma species are among the most promising biological control agents, attracting considerable attention for their diverse antagonistic activity against many plant pathogens. *T. harzianum, T. asperellum,* and *T. virens* have been shown to suppress soil-borne or foliar pathogens in different ways, such as mycoparasitism, competition for nutrients and space,

secretion of antifungal metabolites and cell wall-degrading enzymes and induced systemic resistance (ISR) in host plants. Moreover, *Trichoderma* is compatible with other disease management strategies, including fungicide application, crop rotation, and the cultivation of resistant corn hybrids, and is an ideal component in IDM programmes.

Environmental concerns, stricter pesticide regulations, and the growing prevalence of fungicide resistance have stimulated interest within the biotech community in biologically based crop protection measures. Although *Trichoderma* is excellent at combating soil-borne pathogens, its use in controlling foliar diseases such as northern corn leaf blight has gained momentum in recent years. *Trichoderma* can directly antagonise *E. turcicum* and enhance the plant's innate defense responses, thereby reducing disease severity under greenhouse and field conditions. Research into the biological control mechanisms of *Trichoderma* spp., particularly mycoparasitism, antibiosis, and induced systemic resistance, represents a novel and significant approach to developing effective field-level management strategies against *E. turcicum*. This research addresses the persistent gap between mechanistic laboratory studies and their practical translation into sustainable, long-term disease management strategies for NCLB.

This review summarises the current state of knowledge about *Trichoderma*-based management of NCLB. We discussed the biology and epidemiology of *E. turcicum,* the mechanisms of *Trichoderma*-mediated disease suppression, and practical applications; then we presented the current challenges and the research gaps that are open for the implementation of *Trichoderma*-based biocontrol for sustainable corn production.

LITERATURE SEARCH METHODOLOGY

To ensure systematic and comprehensive coverage of the available literature, relevant papers were extracted from major scientific databases, such as Web of Science, Scopus, PubMed, and Google Scholar. A combination of terms like "*Trichoderma*," "biocontrol," "Northern Corn Leaf Blight," "*Exserohilum turcicum*," "*Setosphaeria turcica,"* "mechanisms of action," "mycoparasitism," "induced systemic resistance," and "sustainable disease management" was used in the search.

Publications from January 2005 to 2025 were included in the search, which captured both early and current developments in the subject. Peer-reviewed original research publications, review papers, and book chapters published in English that particularly discussed *Trichoderma*-mediated biocontrol mechanisms, its use against foliar pathogens, or NCLB management techniques were among the inclusion criteria. Figure 1. Articles unrelated to *Trichoderma*-pathogen interactions, non-peer-reviewed sources, conference abstracts without complete data, and studies without experimental validation were all disregarded. Before the final screening and synthesis, duplicate records across databases were removed.

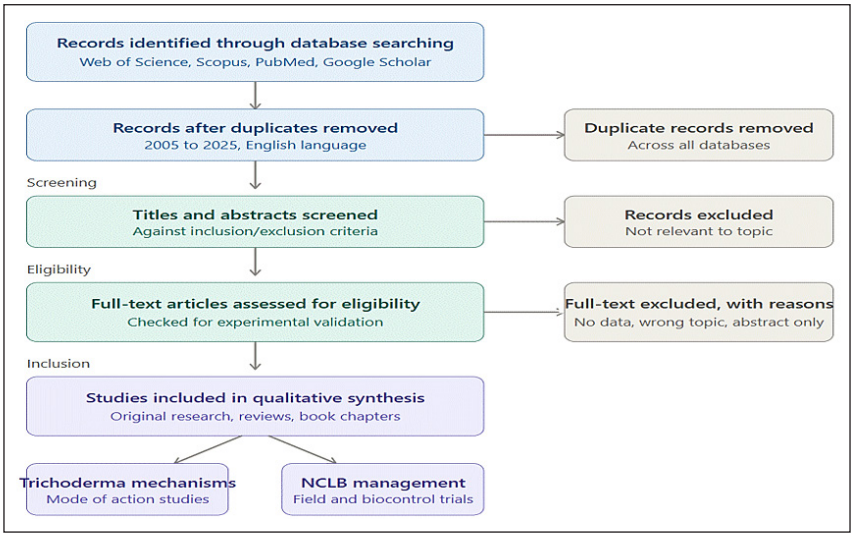


Figure 1. PRISMA flow diagram of the literature search strategy

BIOLOGY AND EPIDEMIOLOGY

Biology

E. turcicum is the anamorphic (asexual) stage of the NCLB pathogen, and *S. turcica* is the teleomorphic (sexual) stage. *E. turcicum* and *S. turcica* are two names for the same species of fungus that were previously described using a dual nomenclature system: *S. turcica* indicates the sexual (teleomorphic/ascosporic) state of this pleomorphic fungus, while *E. turcicum* indicates the asexual (anamorphic/conidial) state. This pathogen is best known for causing NCLB, also known as turcicum leaf blight in corn. It also causes a similar leaf blight in sorghum and other grasses. However, the study of fungal systematics and molecular phylogenetics has led to several taxonomic changes. *E. turcicum* is now placed in the Ascomycota phylum, Dothideomycetes class, order Pleosporales, and family Pleosporaceae. NCLB is a hemibiotrophic fungal pathogen that first begins a biotrophic relationship with the host before progressing to a necrotrophic phase. *E. turcicum* first colonises living host tissue before transitioning to a necrotrophic phase and causing tissue necrosis. The biotrophic phase lasts for about eight days before the fungus transitions to necrotrophy (Human et al., 2020). Under favourable conditions, especially at moderate temperatures (18-28 °C) and with wet leaves, the pathogen produces large conidia on infected leaf tissue. These airborne conidia are easily dispersed by wind and rain splash and can lead to secondary infections of healthy corn leaves and rapid disease spread in and between fields. Host resistance is still an important part of NCLB management.

Although resistant cultivars can be a good way of disease suppression, their durability is limited, and host resistance should be incorporated into other management strategies as part of the IDM programme (Ali et al., 2024).

The pathogen produces conidia that are fusiform to obclavate; although they can also appear ellipsoidal, spindle-shaped, cylindrical, elongated, straight, or slightly curved (Abebe & Singburaudom, 2006). The mature conidia are 52.94-144.12 µm in length and have a distinctive protruding hilum, which is the main characteristic of the genus *Exserohilum* (Anwer et al., 2022). The conidia are pale brown to dark brown, multicellular, and have 1-9 septa, with septation becoming more pronounced as the conidia grow. The conidiophores are solitary and arranged in small groups, and are 47-443 × 4-6 µm in length, cylindrical, septate, flexuous, geniculate, and olivaceous brown in color, with conidia produced terminally at their apices (Anwer et al., 2022). Colony morphology in culture varies with the isolate, culture medium, nutrient composition, and pH. Colonies are usually olivaceous brown, dark brown, grayish brown, or whitish black, reflecting the phenotypic variation among *E. turcicum* isolates under different growth conditions (Anwer et al., 2022).

Disease Development

NCLB disease cycle is shown in Figure 2. The inoculum (conidia) will germinate and develop a germ tube after it lands on the host. Germination is bipolar, and the incubation period is usually 12-24 hours (Ali & Chowdhury, 2014). The infection peg is initiated when the conditions are suitable (Muiru et al., 2008). Once the infection peg has made it through the stomata or cell wall successfully, it colonises both intracellular and intercellular spaces. As a consequence, the pathogen kills the surrounding cells at the site of infection (Ali & Chowdhury, 2014). Conidiophores are usually produced in clusters from the adaxial and abaxial stomata, while single conidia form at the end of the conidiophore, which appears to be dark (Anwer et al., 2022). As a result, symptoms were noted, including small dark spots on the lower leaves that eventually grew into larger ones that ultimately blighted whole leaves (Ali & Chowdhury, 2014). When conditions are unfavourable, *E. turcicum* grows in crop remnants that have not decomposed after harvest.

Infected leaves usually exhibit small, slightly oval, water-soaked symptoms that start on lower leaves and move upwards if no disease control is applied (Agrios, 2005; Ali & Chowdhury, 2014). In severe cases, these tiny spots will grow and unite to form blight symptoms on the entire leaf (Harlapur et al., 2008) and affect the photosynthesis process (Pooja et al., 2023; Swathi et al., 2021). The length of the lesion varies from 2.0 to 15.5 cm, and the width varies from 0.5 to 2.0 cm (Ali & Chowdhury, 2014).

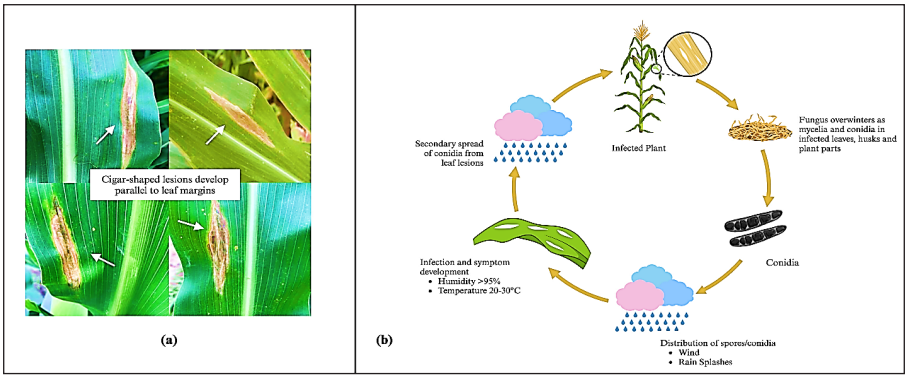


Figure 2. (a) Symptoms of northern corn leaf blight (NCLB) on corn leaves and (b) life cycle of NCLB disease. During overwintering, the use of NCLB as an alternate host on corn leaves leaves conidia and mycelia on the soil surface. However, under warm, humid conditions, infected corn debris produces new conidia, which are the main source of inoculum. Afterward, the NCLB spreads by rain and wind to distant areas and falls on the leaf surface
Source: Adapted and modified (Ijaz & Fan, 2024)

Disease Severity and Yield Loss

The severity of northern corn leaf blight (NCLB) is strongly dependent on the environment (temperature, relative humidity, leaf wetness, rainfall, and altitude (Abebe & Singburaudom, 2006). Good environmental conditions lead to disease development and can cause a significant decline in corn productivity. The reported yield loss due to NCLB ranges from 15% to 66%, depending on disease severity, cultivar susceptibility, and the current environment (Manu et al., 2018). The yield loss is also affected by corn genotype, crop growth stage at the time of infection, pathogen virulence, and environmental conditions. The timing of infection is one of the most important factors in economic damage. Early infection, especially prior to or during tasseling and silking, results in severe damage to the photosynthetically active leaf tissue, and grain filling is severely affected. Infections in the later stages of crop development have a smaller impact on grain yield, as most kernel development has been completed by then. Previous studies have reported that yield losses can be from 28-91% when the disease starts before or around silking, and if it starts 6-8 weeks after silking, yield loss is very low (Swathi et al., 2021).

Weather Factors Influencing Disease Severity

The severity and transmission of disease are influenced by temperature, humidity, rainfall, and wind (Saeed et al., 2023). The number of consecutive wet days, rainfall, relative humidity, and pathogen spore production are positively correlated with climatic conditions (Indira & Muthusubramanian, 2004). As such, Northern corn leaf blight thrives in warm, humid conditions. The highest disease prevalence is observed between 25-30 °C, with

humidity between 75-90% (Saeed et al., 2023). In addition to temperature and the date of sowing, other factors affect disease severity. The disease is more severe at lower elevations than at higher elevations (Abebe & Singburaudom, 2006). The planting date also affects disease severity. Postponing the sowing date is more serious because humidity and temperature are usually higher at lower elevations (Ali et al., 2014). The highest disease severity was found in Karnataka, India, when corn was planted in the September season (Harlapur et al., 2007).

MECHANISMS OF ACTION

The mechanisms of action of *Trichoderma* spp. that reduce foliar and root diseases fall into two broad categories: direct and indirect antagonism. *Trichoderma* is responsible for controlling corn leaf blight mainly through direct antagonism of the pathogen and rapid colonisation of plant tissues before the pathogen forms (Manzar et al., 2024; Yao et al., 2023). In maize, this means rapid growth and competition for space and nutrients, the secretion of antifungal metabolites, and the production of cell wall-degrading enzymes that weaken the blight pathogen (Yao et al., 2023).

A direct mechanism is mycoparasitism. *Trichoderma* attaches to the pathogen hyphae, coils around them, and enters the fungal cell wall. It then releases chitinases, glucanases, proteases, and other lytic enzymes that destroy the pathogen's structure, causing hyphal deformation, lysis, and lack of spore germination (Yao et al., 2023). *Trichoderma* produces volatile and non-volatile secondary metabolites that suppress pathogen growth, slow mycelial expansion, and limit lesion development in corn leaves. Recent studies on corn also show that effective *Trichoderma* strains reduce leaf blight severity and increase defensive enzymes and lignification, thereby conferring stronger resistance to infection (Manzar et al., 2024). In practice, these direct actions reduce pathogen pressure on the leaf surface and in infected tissue, which helps to control blight progression and yield loss (Yao et al., 2023). So, for corn leaf blight, *Trichoderma* is not only a competitor but also a fungal parasite and chemical antagonist to the pathogen (Manzar et al., 2024; Yao et al., 2023). These are particularly effective when these functions are applied in controlled experiments and in contact with fungal pathogens, such as on organic residues, the phyllosphere, and as foliar treatments (Harman, 2006).

Indirect antagonism of *Trichoderma* against corn leaf blight refers to disease suppression through plant-mediated defense rather than only direct contact with the pathogen. In corn, *Trichoderma* colonise s the rhizosphere or root surface and triggers induced systemic resistance, so the plant responds faster and more strongly when leaf blight pathogens attack. For the case of *T. virens* and *P. chlororaphis,* even in the absence of the inoculum on the leaf surface, this priming can lessen the severity of foliar diseases by inducing host resistance. Studies have shown that certain *Trichoderma* strains that interact with roots can initiate induced systemic resistance (ISR), which inhibits the growth of foliage pathogens

(Saravanakumar et al., 2017). This indirect action works mainly through activation of defense enzymes and signalling pathways. There is indirect evidence that, in fodder corn infected with *Bipolaris maydis*, *Trichoderma* treatment increased peroxidase, superoxide dismutase, and catalase activities, which are linked to stronger antioxidant defense and reduced disease severity. The study also noted that *Trichoderma* can stimulate plant defenses through secondary metabolites and other elicitors, supporting systemic resistance against fungal pathogens. Studies have shown that when *Trichoderma* is applied to roots or seeds, it induces ISR, and this reaction is very useful for reducing the severity of foliar diseases (Saravanakumar et al., 2017).

A study showed that *Trichoderma* can rapidly adsorb to the roots of crops for growth, and the hyphae can quickly wrap around the roots of crops to form a protective layer that protects the roots from the invasion of phytopathogens and kills nearby pathogens (Resoli et al., 2022). Some indirect evidence revealed that the growth rate of *T. harzianum* was 2-4.2 times faster than that of *Botrytis cinerea* (Dugassa et al., 2021). Given this nature, T. *harzianum* could easily overcome the pathogen. Herrera-Téllez et al. (2019) found that *Trichoderma* could compete with *Fusarium graminearum* by clinging, twining, interpenetration, and other mechanisms, in which the mycelia of *F. graminearum* were deformed and disappeared. *Trichoderma* can take up water and nutrients, occupy space, and consume oxygen through rapid growth and reproduction, thereby weakening and excluding grey mold pathogens in the same habitat (Herrera-Téllez et al., 2019). A schematic diagram of the mechanism of action of *Trichoderma* spp. against plant fungal diseases is shown in Figure 3.

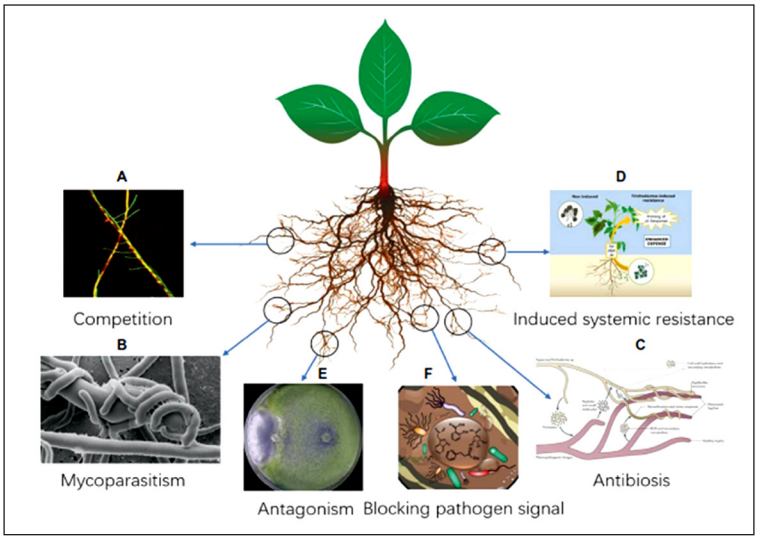


Figure 3. Schematic representation illustrating the mechanisms by which *Trichoderma* exerts biocontrol activity within plant- pathogen interactions
Source: Adapted and modified (Yao et al., 2023)

DISEASE MANAGEMENT

Trichoderma is found everywhere and has great promise and application potential (Tyśkiewicz et al., 2022). It is a filamentous fungus that grows rapidly in tropical soils and plant rhizospheres. *T. harzianum, T. viride, T. asperellum, T. atroviride,* and *T. longibiatum* are the most common species studied and used for biocontrol purposes. *Trichoderma* isolates are used for seed treatments, soil amendments, foliar applications, and as endophytes. They can be formulated as powders, wettable powders, granules, liquid broths, and cell-free filtrates. Some of the features of *Trichoderma spp*. include rapid saprophytic growth (competition), hydrolytic enzymes, secondary metabolite production, the ability to parasitise phytopathogens, plant systemic resistance, growth promotion, and compatibility with fungicides and agricultural practices (Oyesola et al., 2024). Many bacterial and fungal bioagents have been widely used, alone or in combination, for the control of NCLB (Sartori et al., 2017). *Trichoderma spp*. could grow far faster than fungal pathogens (Mohiddin et al., 2021). *Trichoderma* also exhibits several disease-control processes, including parasitism, antagonism, nutrient competition, and the production of substances harmful to pathogens (El-Baky & Amara, 2021). Among them, *T. viride* (Kumari et al., 2020; Subedi et al., 2019), *T. harzianum* (Rani et al., 2022), *T. asperellum* (Limdoltham et al., 2023; Ma et al., 2023), *T. hamatum*, and *T. harzianum* (Limdoltham et al., 2023) are the most likely candidates for the biological components of the IDM programme.

Trichoderma's diverse roles as biocontrol agents, growth promoters, and modulators of the plant microbiome are highlighted by literature reviews and meta-analytical investigations (Harman, 2006). Several studies have reported a significant reduction in NCLB severity and improvement in corn yield. The efficacy of the *Trichoderma* formulations was evaluated through seed treatment, soil application, and foliar spraying (Table 1).

Variations in control efficacy likely reflect strain-specific characteristics and differences in the mechanisms employed. Single-species applications of *T. viride* and *T. asperellum* may rely predominantly on antibiosis and competitive exclusion, resulting in moderate disease suppression (35-55%). In contrast, *T. harzianum* and *Trichoderma* consortium treatments achieved higher disease reduction (45-65%), potentially reflecting the complementary or synergistic effects of mycoparasitism, antibiosis, competition, and induced systemic resistance (ISR). Seed treatment may also provide greater and more consistent protection than foliar application because early establishment of *Trichoderma* in the rhizosphere can facilitate root colonisation and activate ISR before pathogen infection occurs. In comparison, foliar-applied *Trichoderma* is primarily restricted to the treated tissues and may be more vulnerable to environmental factors such as rainfall and UV exposure, which can reduce persistence and colonisation.

Table 1
Efficacy of Trichoderma *spp. and comparative treatments against* Exserohilum turcicum *in corn*

Treatment	Formulation	Mode of Application	Experimental Conditions	Disease Reduction (%)	Observed Effects	Limitations	References
Trichoderma Harzianum (strains T-22, T-1295)	Talc-based powder/conidial suspension for seed coating	Seed treatment	Field and Greenhouse trials on maize; artificial inoculation with *E. turcicum*	45-60%	Reduced lesion size, improved seedling vigour	Efficacy varies with soil moisture/temperature; requires adequate propagule viability; limited persistence in field soils	Harman et al. (2004)
Trichoderma viride	Talc-based formulation / liquid soil drench	Soil application	Pot and field trials on maize seedlings challenged with *E. turcicum*	40-55%	Suppressed *E. turcicum*, enhanced root growth	Sensitive to soil pH and temperature fluctuations; inconsistent rhizosphere colonisation	Kumar & Reddy (2016)
Trichoderma asperellum	Conidial suspension for foliar spraying	Foliar spray	Greenhouse and field trials on maize	35-50%	Lower disease index, increased biomass	Reduced persistence under UV exposure/ rainfall; requires repeated applications	Vinale et al. (2008)
Trichoderma spp. (consortium)	Combined seed coating and soil-applied granules/ suspension	Seed + soil application	Multi-location field trials on maize	50-65%	Induced systemic resistance, higher yield	Higher cost and logistical complexity; strain compatibility must be verified	Mukherjee et al. (2013)
Chemical fungicide (check)	Emulsifiable concentrate / wettable powder	Foliar spray	Standard field trial practice on maize	60-70%	Effective disease control but residue risk	Chemical residues, environmental impact, risk of resistance development	Agrios (2005)
Untreated control	-	-	Same trial conditions, no treatment applied	0%	High disease severity and yield loss	Represents worst-case scenario; not a management option	Shaner & Stromberg (1981)

The discrepancy between greenhouse and field performance further highlights the importance of environmental and ecological factors. Under controlled greenhouse conditions, relatively stable humidity, temperature, and pathogen inoculum levels may favour *Trichoderma* establishment and exaggerate its apparent efficacy. Under field conditions, fluctuating temperature, rainfall, UV exposure, and competition with indigenous microorganisms can substantially reduce colonisation and biocontrol activity. Therefore, while antibiosis and direct competition may contribute substantially to disease suppression under controlled conditions, rhizosphere establishment, mycoparasitism, and particularly ISR are likely to become increasingly important for maintaining *Trichoderma* efficacy under variable and challenging field environments.

PRACTICAL APPLICATION

In-Vitro Studies

In-vitro studies are used to screen potential strains from soil and leaf microenvironments (Sartoria et al., 2015), while Khamari and Beura (2014) found that *T. viride* and *T. harzianum* showed strong suppression effects with percent growth inhibition rate values of 84.7% and 81.7%, respectively, against the tested phytopathogen.

Greenhouse Trial

Many *Trichoderma* species were tested using seed treatments, soil drenches, root inoculations, and foliar sprays in greenhouse and growth-chamber experiments. Studies have shown that seedlings treated with *Trichoderma* have higher growth and biomass and fewer disease lesions (e.g., after artificial inoculation with E. *turcicum*). Seed treatments with *T. harzianum* reduced pathogen colonisation in seedlings, and pot experiments with *T. asperellum* showed it protected them from *E. turcicum.* These data support the notion that induced systemic resistance (ISR) is in concert with direct hostile activity (Ma et al., 2023).

Field Trials

Field experiments of *Trichoderma* for NCLB disease control produced mixed but encouraging results. *T. asperellum* strain 576 significantly reduced *E. turcicum* disease infections and promoted corn seedling growth under field settings. Similarly, the wet formulation of endophytic *Trichoderma* was shown to successfully control NCLB compared with the dry formulation, and it is clear that both formulation and viability are important factors in field applications (Ma et al., 2023). Wang et al. (2025) reported a 72% decrease in NCLB disease incidence after treatment with *Trichoderma* in combination with difenoconazole (low rate); therefore, the fungicide treatment strategy should be effective and can be integrated with *Trichoderma* to reduce chemical dosage and increase control efficacy.

However, the fungicide tolerance and compatibility of the specific strain of *Trichoderma* used is important (Wang et al., 2025). Ma et al. (2023) conducted a comprehensive field study that showed corn seedlings injected with or treated with both *E. turcicum* 101 and *T. asperellum* 576 showed major improvement after being treated with a 10^7-spores/mL conidial suspension using foliar spraying and soil drenching. This indicates that *T. asperellum* 576 is a very promising strain. It has the potential to be an effective biocontrol agent in the control of diseases, as it acts as an inhibitor of the production of inhibitory chemicals and stimulates plant growth. Table 2 summarises the field disease control efficacy of NCLB. Biological antagonists, such as *Trichoderma*, reduce the incidence of corn diseases in a variety of agricultural studies. However, the differences in performance are largely due to local climate variations, fungal strain variations, product formulation, and application timing (Limdolthamand et al., 2023; Subedi et al., 2019). Moreover, control efficacy varies considerably among studies because of differences in *Trichoderma* strains, pathogen isolates, inoculum density, and application methods, including seed, foliar, and soil applications, making direct comparisons difficult. Environmental factors such as temperature, relative humidity, soil pH, and competition within the rhizosphere can further influence *Trichoderma* colonisation, establishment, and antagonistic activity, potentially explaining differences in performance across locations. Among the evaluated species, *T. harzianum* and *T. asperellum* appear to show relatively consistent biocontrol potential, possibly due to their ability to employ multiple complementary mechanisms, including mycoparasitism, hydrolytic enzyme production, antibiosis, competition, and induction of plant defence responses. However, reproducibility across studies remains limited because of non-standardised bioassays, differences in experimental conditions, insufficient field validation, and the frequent reliance on laboratory-based inhibition assays. Therefore, claims regarding the comparative superiority of particular *Trichoderma* strains or species should be interpreted cautiously, and robust conclusions require standardised methodologies and replicated multi-location, multi-environment field trials under realistic disease and environmental conditions.

FORMULATION AND DELIVERY OF *TRICHODERMA*

Seed Treatment

Trichoderma spores are very practical to use as a seed coating. Early root colonisation and ISR can be achieved in the early stages of plant growth, which is also simpler and relatively inexpensive. This kind of seed treatment has been shown to be effective against a variety of corn diseases and is widely used to control early-season diseases and seedborne pathogens. However, seed coating always requires fresh, viable spores and can be integrated with other seed treatments, such as insecticides or fungicides (Mastouri et al., 2010).

Table 2
Field application of single and consortia of Trichoderma *spp. for controlling corn disease*

Treatment	Strain Origin	Formulation	Mode of Application	Experimental Conditions	Observed Effects	Limitations	References
Trichoderma harzianum	Soil-derived rhizosphere isolate (maize rhizosphere)	Talc-based powder seed coating (1×10^8 cfu/g)	Seed treatment	Greenhouse pot trial + multi-location field trial, maize, natural + artificial inoculation with *E. turcicum*	Reduced lesion size, improved seedling vigour	Efficacy varies with soil temperature/ moisture; needs viable seed coat contact	Harman et al. (2004)
Trichoderma Viride	Rhizosphere soil isolate	Liquid spore suspension (1×10^7 spores/mL)	Soil application	Field trial, maize, natural epiphytotic conditions	Suppressed *E. turcicum*, enhanced root growth	Slower onset of protection; repeat application often required	Kumar & Reddy (2016)
Trichoderma asperellum	Endophytic/ rhizosphere isolate	Aqueous spore suspension (foliar grade)	Foliar spray	Greenhouse + field trial, maize	Lower disease index, increased biomass	Spore viability reduced by UV exposure and low leaf-surface humidity	Vinale et al. (2008)
Trichoderma spp. (consortium)	Multi-strain synergistic combination	Combined talc (seed) + liquid (soil) formulation	Seed + soil application	Multi-season field trials, maize	Induced systemic resistance, higher yield	Strain compatibility/ shelf-life challenges; higher production cost	Mukherjee et al. (2013)
Chemical fungicide (check)	synthetic compound	Emulsifiable concentrate / wettable powder	Foliar spray	Field trial, corn, standard agronomic practice	Effective disease control but residue risk	Chemical residues, non-target/ environmental toxicity, resistance risk	Agrios (2005)
Untreated control	-	-	-	Same trial conditions, no treatment applied	High disease severity and yield loss	Not applicable (reference treatment)	Shaner & Stromberg (1981)

Soil Amendments and Foliar Spray

Soil drench is widely used in greenhouse studies, and this method achieves high-scale root colonisation and disease control efficacy. However, granular and liquid formulations are commonly used under field settings and adopted during planting or in-furrow systems. In foliar spray treatment, *Trichoderma* spores are inoculated directly onto the corn leaf surface to produce antifungal chemicals or to prevent *E. turcicum* spores from germinating. Protective formulations, in addition to adhesion agents, were applied during late evening to improve the survival rate of *Trichoderma* strains on the leaf surface. This practice significantly increases the likelihood of successful outcomes, given that the phyllosphere is a challenging environment (e.g., UV radiation, moisture loss). Foliar treatments have been shown to reduce the spread of disease lesions in field experiments. However, persistence on the leaf surface is generally lower than in soil-root systems and is therefore more susceptible to repeated applications (Limdolthamand et al., 2023).

Wet and Dry Formulations

Fresh or wet formulations (e.g., wettable powders and liquid fermentation) can be more effective in the field than dry formulations. Dry formulations (such as powders and granules) have logistical advantages in terms of storage and transportation. However, spore viability, proper drying procedures, and carrier selection are required. According to sweet corn field testing, fresh formulations inhibited northern corn leaf blight (NCLB) more successfully than dry powders did for some strains (Limdolthamand et al., 2023).

INTEGRATED DISEASE MANAGEMENT

Compatibility with Host Resistance

Trichoderma provides a multi-faceted defense strategy in NCLB disease control. It can be incorporated with host resistance via gene pyramiding and quantitative resistance to avoid reliance on individual resistance genes. This is because the plant will respond, to a lesser extent, to specific major-gene resistance pathways and to *Trichoderma* ISR, which can enhance the host's genetic defense capability. Field tactics should emphasise resistant hybrids in combination with *Trichoderma* (Ali et al., 2024).

Compatibility with Fungicides

Fungicides are commonly used in the NCLB disease management programme. While some fungicides are proven compatible with *Trichoderma* spp*.,* others can inhibit the growth of these beneficial fungi. There has been evidence that *Trichoderma* application can lower the dosage of synthetic fungicides (difenoconazole) and lead to additive or complementary effects in NCLB disease control. This strategy reduces the use of fungicides while still providing effective disease control. Before using combined treatments, compatibility testing

should be conducted in controlled laboratory settings or under field conditions. The other important factor is the timing of application (Wang et al., 2025).

Cultural Practices and Residue Management

Effective residue management, such as tillage, residue removal, and rapid decomposition, can reduce the amount of pathogen inoculum and increase the effectiveness of biological control measures since *E. turcicum* inoculum remains on crop residues after the harvesting stage. Interestingly, applying *Trichoderma* to corn residues not only accelerates decomposition but also reduces the pathogen's survival rate. However, the effectiveness of residue management systems that favour *Trichoderma* colonisation may vary with climatic conditions and specific cropping systems. Thus, it is logical to integrate residue management strategies with *Trichoderma* applications from an epidemiological perspective (Wang et al., 2025).

Response/Addition Regarding PR Genes and R Genes

The activation of plant innate immune pathways, particularly through the upregulation of pathogenesis-related (PR) genes and modulation of resistance (R) gene-mediated defence, is closely associated with *Trichoderma*-mediated resistance in maize against NCLB caused by *E. turcicum*. Following root or foliar colonisation, *Trichoderma* spp. can induce systemic resistance (ISR), leading to enhanced expression of defence-related genes, including *PR-1*, *PR-2* (β-1,3-glucanase), *PR-3* (chitinase), and *PR-5* (thaumatin-like proteins). The products of these genes contribute to cell-wall reinforcement and the inhibition of pathogen growth. In addition, R genes encoding nucleotide-binding site- leucine-rich repeat (NBS-LRR) proteins play important roles in pathogen recognition and activation of downstream defence responses. *Trichoderma* colonisation may prime these defence pathways, enabling maize plants to mount a faster and stronger response following *E. turcicum* infection. This molecular perspective complements the direct biocontrol mechanisms discussed earlier and provides a more comprehensive understanding of how *Trichoderma*-mediated ISR may contribute to the suppression of NCLB.

LIMITATIONS AND KNOWLEDGE GAPS

Variable Field Efficacy

The main limitation is that performance varies from field to field. Extreme temperatures, ultraviolet radiation, drought conditions, soil and leaf microbiomes, and agricultural practices were major factors affecting the establishment and long-term survival of *Trichoderma* spp. To assess reliability and identify resilient strains suited to various agroecological conditions, the experiments should be conducted across multiple locations and over multiple years (Limdolthamand et al., 2023). The effectiveness of *Trichoderma* in controlling the NCLB of corn is summarised in Table 3.

Table 3
Research gaps regarding the effectiveness of Trichoderma *spp. in controlling the NCBL of corn*

Research Gap	Description of Gap	Causes	Remark & References
Limited field-level efficacy data for *Trichoderma* against NCLB	Most studies are conducted under *greenhouse or lab conditions*; robust multi-location field trials across diverse environments are scarce.	Field factors (climate, soil microbes) can significantly alter biocontrol performance compared to controlled conditions.	Endophytic *Trichoderma* spp. tested in initial field trials, but broader validation is still needed (Limdolthamand et al., 2023)
Comparative performance of different *Trichoderma* strains	Few comparative studies evaluate multiple *Trichoderma* species or isolates for antagonism against *E. turcicum*	Identifying the most effective strains is essential for reliable biocontrol product development.	*T. asperellum* 576 shown to suppress *E. turcicum* but other isolates less characterised (Ma et al., 2023)
Mechanistic understanding of biocontrol action	Underlying modes of action (e.g., systemic induced resistance vs antibiosis vs competition) of *Trichoderma* on NCLB interaction is poorly resolved.	Understanding mechanisms helps optimise formulation and predict efficacy under stress.	While antagonism is reported, detailed host- biocontrol mechanisms are not fully elucidated (Ma et al., 2023)
Integration with existing disease management practices	Few studies explore interactions between *Trichoderma* applications and fungicides or other cultural practices in NCLB control.	Synergistic or antagonistic effects with agrochemicals need evaluation for integrated pest management (IPM).	Combined *Trichoderma*-fungicide treatments show promise, but comprehensive analysis is limited (Wang et al., 2025).
Long-term effects on corn yield and soil microbiome	Long-term impacts of repeated *Trichoderma* application on yield stability and soil microbial communities remain largely unexplored.	Sustainable use requires understanding soil ecology and crop performance over seasons.	Most studies focus on short-term disease suppression rather than multi-season outcomes. (Inferred from lack of longitudinal data)
Effectiveness under varying environmental conditions	The efficacy of *Trichoderma* across environments (e.g., humidity, temperature gradients) is underreported.	NCLB severity and biocontrol performance is both highly influenced by environmental conditions.	Existing field data limited to specific regions; broader climatic range missing (Limdolthamand et al., 2023)
Standardisation of formulations and application methods	There is a lack of standardised protocols for formulations (fresh vs dry), dosages, and application timing for NCLB control.	Standard protocols are needed for reproducibility and commercialisation.	Fresh formulations showed better effects than dry in one study (Limdolthamand et al., 2023)
Host plant responses (molecular and physiological)	Limited insights into how maize defense pathways are *activated or modified* by *Trichoderma* in the context of NCLB.	Molecular markers could serve as indicators of effective biocontrol and selection tools.	Mechanistic studies for other diseases (e.g., SCLB) exist, but NCLB-specific host responses are less studied (Lang et al., 2025)

Interactions with Synthetic Fungicides

Some fungicides and pesticides can suppress *Trichoderma* activity. There is ongoing research on finding compatible chemical formulations with appropriate tank-mix combinations and the best application sequence, whether to apply *Trichoderma* before or after fungicide treatment. A comprehensive study to uncover differences in fungicide tolerance between different strains indicates that compatibility testing is required for each strain (Korkom & Ünal, 2025).

Standardisation of Trials

Introducing standard protocols for strain assessment, formulation evaluation, and field trial reporting should accelerate progress in this field. Experimental designs, inoculation methods, and disease assessment techniques vary across studies. Establishing standard operating practices for these areas would advance disease control programmes (Sartoria et al., 2015).

FUTURE PERSPECTIVE AND CONCLUSION

Future research should investigate the interactions between different *Trichoderma* strains to identify complementary mechanisms of action and improve environmental resilience (Sartori et al., 2017). Comprehensive evaluations of the compatibility between fungicides and beneficial *Trichoderma* strains are also essential for developing integrated disease management strategies that reduce chemical inputs while maintaining effective disease control (Wang et al., 2025). To improve the effectiveness of biocontrol, future studies on *Trichoderma* spp. in controlling NCLB should combine omics-driven strategies with cutting-edge biotechnology. While metabolomics aids in the discovery of novel secondary metabolites with antifungal potential against *E. turcicum*, genomics and transcriptomics can identify antagonistic gene clusters and expression patterns triggered during pathogen-host interaction.

To improve disease suppression and plant resistance, microbiome engineering offers an opportunity to create synthetic consortia that combine *Trichoderma* with beneficial rhizobacteria. Precise strain improvement by CRISPR-based gene editing may increase mycoparasitism, induced systemic resistance, and stress tolerance features. Field effectiveness and commercial feasibility will be enhanced by developments in bioformulation technologies, such as nanoencapsulation, nanocarriers and shelf-stable spore formulations. AI-assisted strain selection can speed up the identification of better biocontrol candidates by screening genomic and phenotypic data using machine learning. Including these developments within a precision agriculture framework, such as remote sensing and site-specific application, will optimise *Trichoderma* deployment, ensuring targeted,

sustainable, and climate-resilient management of NCLB in corn production systems worldwide. In addition, molecular biomarkers and biochemical indicators that predict corn responses to ISR should be identified to improve the selection and monitoring of effective treatments. Greenhouse experiments should be validated using field-based data to ensure practical applicability under commercial farming conditions (Saravanakumar et al., 2017). Finally, participatory on-farm trials involving farmers, together with economic assessments of adoption barriers, supply chain logistics, and market acceptance of *Trichoderma*-based products, are necessary to support large-scale implementation (Sartori et al., 2017).

In conclusion, the synergistic effects of *Trichoderma* treatments in corn production systems are scientifically supported and represent an environmentally sustainable approach for managing NCLB. *Trichoderma* effectively suppresses disease through direct antagonism, antibiosis, and ISR, thereby reducing disease severity, enhancing host resistance, and lowering dependence on chemical fungicides. Although laboratory, greenhouse, and field studies have demonstrated promising results, successful field implementation depends on appropriate strain selection, effective formulation, suitable application methods, and favourable environmental conditions. Therefore, an integrated management strategy that combines well-adapted *Trichoderma* strains, optimised formulations, compatibility with fungicides and agronomic practices, and incorporation into comprehensive disease management programmes is recommended. Continued research, together with close collaboration among researchers, extension services, and farmers, will be essential to maximise the potential of *Trichoderma* as a sustainable and scalable solution for the management of northern corn leaf blight.

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Comparison of Steamed and Non-Steamed Parboiled Rice Dried at Different Superheated Steam Drying Temperatures

Ria Natasha Shasazmila Zahurin[1], Rumaisa Nordin[1]*, Iffah Nadhira Madzuki[1], Nurul Nadiah Najmudin[1], and Lai Hoong Cheng[2]

[1]Faculty of Chemical Engineering and Technology, Universiti Malaysia Perlis (UniMAP), UNICITI Alam Campus, 02100 Sg. Chucuh, Padang Besar, Perlis, Malaysia

[2]Food Technology Division, School of Industrial Technology, Universiti Sains Malaysia (USM), 11800 Gelugor, Pulau Pinang, Malaysia

ABSTRACT

Parboiled rice is produced by soaking, steaming and drying the rice grain. This process can enhance the dietary advantages of rice due to changes in the structure of starch and retention of nutrients. However, the conventional parboiling procedure is challenging and time-consuming, as it involves multiple steps, including soaking and steaming, thereby increasing processing time and energy consumption. Hence, there is a need to explore alternative processing technologies that could reduce or eliminate the steaming stage, thereby simplifying the process while maintaining rice quality. In this study, rice soaked, steamed and dried by superheated steam drying (SSD) at different temperatures was compared with rice dried at the same temperatures without the steaming step. The samples were measured for the amylose content, head rice yield, starch crystallinity and antioxidant properties. Samples of rice that were steamed before SSD drying demonstrated better starch structure, thermal behaviour, and milling quality than samples that were dried without steaming. Among the treatments, the rice sample dried at 100°C showed desirable characteristics such as lower amylose concentration, higher head rice yield and moderate crystallinity. Overall, SSD effectively modifies rice starch structure while preserving good milling quality and antioxidant properties, with steamed samples having better overall quality than those treated without steaming.

Keywords: Amylose content, antioxidant activity, head rice yield, parboiled rice, starch crystallinity, superheated steam drying

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E-mail addresses:
rianatasha@studentmail.unimap.edu.my (Ria Natasha Shasazmila Zahurin)
rumaisa@unimap.edu.my (Rumaisa Nordin)
iffahmadzuki@unimap.edu.my (Iffah Nadhira Madzuki)
nadiahnajmudin23@gmail.com (Nadiah Najmudin)
lhcheng@usm.my (Lai Hoong Cheng)
* Corresponding author

INTRODUCTION

Rice is a major source of carbohydrates for the world's population, especially in Asian

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countries where rice consumption is highest. There are wide varieties of rice with different processing techniques such as white rice, brown rice, glutinous rice, and parboiled rice (Bana et al., 2020), with white rice being the most consumed. Due to growing health awareness among consumers, the demand for healthier rice varieties such as parboiled rice is increasing.

Parboiled rice is rich in nutrients and has a delayed digestion rate, which makes it a better option for consumer (Li et al., 2021). The soaking and steaming process transfers nutrients from the bran to the endosperm, hence retaining nutrients (Taleon et al., 2022). Usually, parboiling treatment is carried out as a sequential process of soaking, steam treatment and drying before milling. Soaking allows water uptake, steaming gelatinises starch and plugs fissures, and drying restores hardness, enhancing grain structure and stability in storage. However, traditional methods frequently do these processes independently, which are time and energy-consuming and lead to variable rice quality (Muchlisyiyah et al., 2023; Yousaf et al., 2017).

Superheated steam drying (SSD) is a technique that is more efficient alternative, combining steaming and drying into a single operation (Muchlisyiyah et al., 2023). Indeed, SSD is a process of soaking raw paddy for uniform moisture, followed by steam and then drying at an optimum temperature. It provides uniform heat in a short time and saves energy (Jittanit & Angkaew, 2021). Steam acts like other hot gases and can efficiently dry high-moisture paddy by releasing sensible and latent heat (Muchlisyiyah et al., 2023). This technique leads to a development of the target product quality with a reduction in processing time (Fang et al., 2023). SSD also controls oxidation of food by preventing lipid oxidation and formation of hazardous chemicals using a low-oxygen atmosphere, keeping flavour, and extending shelf life (Fang et al., 2023; Yodkaew et al., 2017).

Although SSD has several advantages, the effects of SSD temperature on parboiled rice quality have not been well studied. Conventional parboiling is inefficient, with distinct soaking, steaming, and drying procedures that need significant energy and long processing periods. High-temperature soaking and steaming can induce unwanted colour changes and reduced consumer approval (Muchlisyiyah et al., 2023; Yousaf et al., 2017). The drying process is typically the most time-consuming, and solar drying might take as long as five days depending on the weather (Chen et al., 2025). Soybean drying using SSD showed a faster and more reliable alternative drying method. Compared with hot air drying, SSD can save energy consumption and enhance heating efficiency (Prachayawarakorn et al., 2006).

Consequently, this study aim to assess how different SSD conditions influence parboiled rice quality, focusing on temperature effects and a comparison of steam- and non-steamed samples. The study seeks to optimize SSD processing parameters based on rice quality attributes, including starch gelatinisation, water reduction, and textural properties of cooked parboiled rice.

MATERIALS AND METHODS

Sample Collection

MR 315 paddy was collected from a local field in Kodiang, Kedah, Malaysia, on 10 February 2025. The grains were vacuum-packed and stored in a chiller at 10 °C until further use.

Parboiled Rice Preparation

Paddy samples were weighed (200 g) and added to 700 mL of water in a beaker. The beaker was then placed in a water bath set at 70 °C for 3 hours. For the steamed rice sample, the rice sample was steamed for 15 minutes after being soaked (Onmankhong et al., 2021). In addition, a non-steamed sample was also prepared under the same soaking conditions to serve as a comparison without steaming.

Superheated Steam Drying Process

After being soaked, the paddy samples were spread evenly on baking paper, placed on a stainless-steel tray and loaded into the dryer (Sharp Healsio Superheated Steam Oven-AX1600VMR). The soaked samples were dried using superheated steam at 100 °C, 120 °C, and 140 °C until 12% moisture content was achieved. This was done to observe the overall quality attributes of paddy rice under different temperature conditions.

Dehusking Process

The dehusking process was done by removing the outer husk of the paddy using an Electrical Vertical Rice Husking Machine (JLGJ-45), allowing for subsequent quality analysis.

Determination of Head Rice Yield

Head rice yield (HRY) is the mass percentage of rough rice remaining as head rice, which is an indicator of rice quality. A 20 g sample of rice kernel was sieved to separate the broken rice kernels from full-length rice kernels. All rice samples were carried out in triplicate. The full-length rice kernels were weighed and calculated with the following Equation 1 (Meresa et al., 2020)

$$Head\ Rice\ Yield\ (\%) = \frac{Weight\ of\ head\ rice\ (g)}{Weight\ of\ total\ rice\ sample\ (g)} \times 100 \qquad [1]$$

Amylose Content (%)

The iodine colorimetric method was used to determine the amylose content of the rice samples. About 100 mg of finely ground rice flour was mixed with ethanol and an alkaline solution, heated to gelatinise the starch, and then reacted with a standard iodine- potassium iodide solution to form the distinctive amylose- iodine complex. The resulting blue colour was measured spectrophotometrically at 620 nm using a UV-Vis spectrophotometer (Lambda 365+, PerkinElmer, USA) and compared to a calibration curve made from certified amylose concentrations (Martins et al., 2021).

Crystalline Structure Analysis

An XRD (PANalytical, X'Pert3 Powder, Netherlands) operating at 40 mA and 40 kV was used to get the X-ray patterns of parboiled rice. At room temperature (25 °C), the diffraction angle (2θ) ranged from 5°θ to 65°θ at a rate of 0.05°θ/min. The sample holder was firmly filled with the rice powder. The Savitzky-Golay method was used to smooth the diffractogram curves. The diffractogram was convoluted using the Gaussian response function to expose the amorphous region (Almeida et al., 2019).

Cooked Parboiled Rice Preparation

The optimal drying temperature of the selected dryer was determined by cooking in an electric rice cooker (Milux, model MRC-510SE, Malaysia) at a rice-to-water ratio of 1:3, by volume. After cooking, the parboiled rice is collected by removing the strainer and cooled until it reaches room temperature (approximately 25 °C). The cooked rice was freeze-dried using a freeze dryer (Memmert, Model UF110) for 24 hours before further analysis.

Rice Samples Extraction

Prior to analysis, 10 mL of distilled water and 1 g of rice powder were combined, and the mixture was left for five minutes. The combination was centrifuged for 15 minutes at 5000 rpm, and the supernatant was collected for further analysis of total phenolic content (TPC) and antioxidant analysis (Priyanthi & Sivakanesan, 2021). The total phenolic content (TPC) and antioxidant activity (DPPH) of the selected rice samples, both 100 °C steam-treated and non-steam-treated, and commercial parboiled rice were evaluated. Based on the evaluation of physicochemical and structural characteristics of samples, treatment at 100 °C was selected for further comparison.

Total Phenolic Content Determination

The total phenolic content was assessed using the Folin-Ciocalteu technique. Initially, 1000 ppm gallic acid stock solution was prepared by dissolving 100 mg in 100 mL of distilled

water, and standard solutions (0, 20, 40, 60, 80, 100, 150, and 200 ppm) were prepared by dilution. For the standard curve, 1 mL of each solution was combined with 5 mL of Folin-Ciocalteu reagent, vortexed, allowed to stand for 3 to 5 minutes, followed by the addition of 4 mL of 7.5% (w/v) Na_2CO_3, and incubated at room temperature (25 °C) for 2 hours prior to measuring absorbance at 765 nm. A reagent blank was prepared using 1 mL of distilled water, 5 mL of Folin-Ciocalteu reagent, and 4 mL of Na_2CO_3. Samples were analysed in triplicate to ensure validation of the experiment.

Antioxidant Activity Determination

A newly prepared DPPH working solution (2850 µL) was mixed with 150 µL of sample and allowed to react in the dark cabinet for 30 minutes. The absorbance of the mixture was measured at 515 nm using a ultraviolet-visible (UV-Vis) spectrophotometer (LAMBDA 365+, PerkinElmer, USA). Methanol served as a blank, whereas the control sample consisted only of methanol with a diluted DPPH stock solution (Abd. Razak et al., 2021). The following Equation 2 was used to determine the proportion of scavenging activity.

$$DPPH\ Radical\ Scavenging\ Activity(\%) = \frac{A\ blank - A\ sample}{A\ blank} \times 100 \quad [2]$$

Statistical Analysis

The data from each treatment group were subjected to two-way Analysis of Variance (ANOVA) to assess the impact of SSD temperature and duration on the evaluated quality parameters. Upon identifying significant differences using ANOVA, Tukey's Honestly Significant Difference (HSD) test was utilised to compare the treatment means. All results were presented as mean ± standard deviation, and differences were considered significant at $p<0.05$ (Tao et al., 2020) using Microsoft Excel and GraphPad Prism.

RESULTS AND DISCUSSION

Head Rice Yield of Parboiled Rice

The present study evaluated the quality of parboiled rice samples dried using superheated steam drying (SSD) at different drying temperatures, and head rice yield (HRY) is a key indicator to assess the overall quality of rice grains. Table 1 shows that the steamed sample at 100 °C produced a high HRY (90.61%) compared to the non-steamed sample (77.26%). This could be due to the starches being gelatinised to minimise fissuring and reduce the susceptibility to milling breakage in the parboiled end-product (Wang et al., 2018). The data suggest that fissures formed during soaking were not sealed due to incomplete

Table 1
Percentage of head rice yield for steam and non-steam parboiled rice

	100 °C	120 °C	140 °C
Steam	90.61 ± 3.3^{Aa}	91.86 ± 2.4^{Aa}	87.21 ± 0.7^{Aa}
Non-steam	77.26 ± 0.3^{Ba}	66.76 ± 1.3^{Bb}	73.66 ± 1.0^{Ba}

Note. $^{A, B}$ Within a column means that values without a common superscript differ ($P<0.05$)
^{a,b} Within a row means that values without a common superscript differ ($P<0.05$)

gelatinisation while steaming (Buggenhout et al., 2014), highlighting a significant difference ($p<0.05$) between the two processing procedures. There was no significant difference ($p >0.05$) across temperatures in the same treatment, indicating that the processing method did not influence the HRY more than temperature. For the non-steam treatment, HRY was significantly decreased at 120 °C (66.76%) as compared to 100 °C (77.26%) and 140 °C (73.66%) ($p < 0.05$). This reduction could be attributed to the increased susceptibility of the rice kernels to fissure and breakage under the 120 °C drying condition. However, the HRY at 140 °C increased to 73.66%, and no significant difference was observed from 100 °C ($p > 0.05$). In contrast, the steamed samples showed no significant difference in HRY across the three drying temperatures ($p > 0.05$), indicating that the steaming treatment may have reduced the susceptibility of the kernels to temperature-related milling damage.

Amylose Content Percentage

Table 2 shows that the highest percentage of amylose content was obtained at 100 °C for the drying of the non-steamed rice sample (59.84%), whereas the steamed rice sample dried at 100 °C exhibited the lowest amylose content (46.80%). The unexpectedly lower amylose value in the steam-treated rice might be due to the combined effects of heat and moisture (Gong et al., 2024) that disrupted starch crystallinity (Yang et al., 2019), allowing amylose to leach out from the granules and redistribute throughout the endosperm matrix (Huang et al., 2012). Consequently, less amylose remained available within the rice granules obtained from the analysis. Thus, steamed-rice samples with lower amylose content have softer grains, which leads to fewer fissures during milling and thus higher head rice yield (Kalpanadevi et al., 2019). However, the non-steam treatment created less moisture penetration, retained more amylose inside the granule matrix, resulting in greater identified amylose content during analysis (Park et al., 2017). This study also observed that the relationship of amylose content was negatively correlated with head rice yield. The amylose content of the steamed samples numerically increased to 59.43% and 58.81% at 120°C and 140°C, respectively. The non-steamed samples decreased to 47.25% and 48.49%, respectively. However, these changes across temperature levels were not statistically significant within the respective treatments ($p > 0.05$). In contrast, significant

differences were observed between the steam and non-steam treatments at both 120 °C and 140 °C ($p < 0.05$). Therefore, within the range studied, the treatment condition had a greater effect on the measured amylose content than did drying temperature. The lack of a significant effect of temperature may be due to the small changes in amylose leaching within the temperature range studied, as partial gelatinisation may not have shown distinct differences at the different temperatures (Chumsri et al., 2022). The results therefore suggest that the effect of moisture availability and changes in the structure of the starch induced by steaming were more influential on amylose leaching than the drying temperature itself.

Table 2
Amylose content (%) for rice samples at temperatures 100 °C, 120 °C, and 140 °C

	100 °C	**120 °C**	**140 °C**
Steam	46.80 ± 8.7^{Aa}	59.43 ± 2.0^{Aa}	58.81 ± 0.8^{Aa}
Non-steam	59.84 ± 5.6^{Aa}	47.25 ± 1.0^{Ba}	48.49 ± 0.9^{Ba}

Note. $^{A, B}$ Within a column means that values without a common superscript differ ($P<0.05$)
^{a,b} Within a row means that values without a common superscript differ ($P<0.05$)

Comparison of Optimum SST Temperature and Commercial Parboiled Rice

The rice sample treated with steam at 100 °C was chosen as the rice sample that obtained the optimum temperature for further comparison because the treatment displayed the lowest amylose content, which is beneficial for producing a lower glycaemic index. This sample had a higher head rice yield (90.61%) and lower amylose content (46.80%) than the non-steam sample at 100 °C. The XRD analysis showed that the crystallinity index of the steam-treated sample was 54.25% compared to 72.00% and 19.90% of the non-steam sample and commercial parboiled rice, respectively, as presented in Table 3. The decrease in crystallinity index of the steam-treated sample as compared to the non-steam sample indicated that the combined effect of heat and moisture during steaming disturbed the ordered structure of starch.

The XRD results should be interpreted separately from the DSC results, as the two techniques give different information on starch structure. XRD measures the relative crystalline order of starch. DSC measures the thermal energy associated with the disruption of thermally detectable ordered structures during gelatinisation. Thus, the gelatinisation enthalpy (ΔH) should not be used as a direct measure of the crystallinity index obtained from XRD. The ΔH of the steam-treated sample in this study was 254.4

Table 3
Crystallinity index (%) for steam and non-steam rice samples at 100 °C and commercial parboiled rice

	100 °C
Steam	54.25%
Non-steam	72.00%
Commercial Parboiled Rice	19.90%

J/g, and the non-steam sample was 110.5 J/g, much lower. Commercial parboiled rice had the highest ΔH (263.2 J/g) and the lowest XRD crystallinity index (19.90%). The results showed that the trend of XRD crystallinity index and DSC gelatinisation enthalpy was not the same in the samples. Thus, the two analyses provide complementary information for understanding the structural and thermal characteristics of parboiled rice.

X-ray Diffraction (XRD) is a conventional method employed to characterise changes in the crystallinity of starch. This investigation identified specific diffraction peaks at around 15°, 17°, 18°, and 23° (2θ), signifying a characteristic A-type crystalline structure often associated with rice starch (Zhang & Zhang, 2019). The crystallinity index of rice was 54.25% after steam treatment, whereas the sample without steam treatment had a higher index of 72.00%. The lower crystallinity index of the steam-treated sample could be due to the synergistic effect of heat and moisture that can break the ordered regions of starch during processing (Guo et al., 2023). In contrast, the non-steam sample has a higher crystallinity index and a better retention of detectable crystalline order. Commercial parboiled rice showed the lowest crystallinity index (19.90%), indicating that the crystalline structure of starch was significantly affected by the industrial parboiling process (Cheng et al., 2019). These extreme conditions caused extensive starch gelatinisation, which disrupted more A-type crystalline regions and resulted in a reduced crystallinity index (Kwofie & Ngadi, 2017).

Characteristics of Parboiled Rice

Rice starch's thermal characteristics were evaluated using DSC, measuring the onset temperature (T_o), peak temperature (T_P), and gelatinisation enthalpy (ΔH), as shown in Figure 1, which provide information about starch crystallinity, molecular order, and thermal stability. The corresponding thermal parameters are presented in Table 4. The T_o values of the steam, non-steam and commercial parboiled rice samples were similar and ranged from 31.00 °C to 31.51 °C. The T_P values were similarly in the range of 39.57-41.47 °C. The transition temperatures are relatively close, indicating the samples had similar thermal transition ranges under the conditions of the DSC analysis.

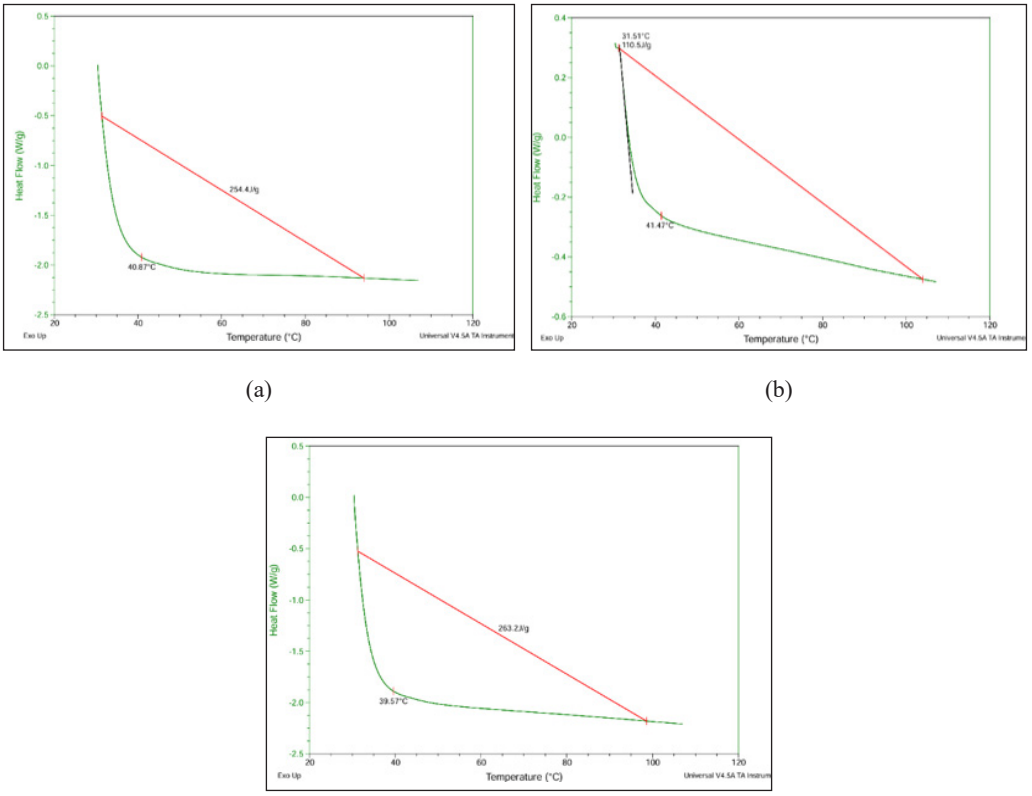
However, gelatinisation enthalpy (ΔH) varied considerably between samples. The ΔH of the steam-treated sample at 100 °C was determined to be 254.4 J/g, while that of the non-steam sample was significantly lower at 110.5 J/g. The commercial parboiled rice had the highest ΔH at 263.2 J/g. The ΔH

Table 4
Onset Temperature (T_O), Peak Temperature (T_P), and Gelatinisation enthalpy (ΔH) of steam and non-steam rice samples at 100 °C and commercial parboiled rice

	Steam	**Non-steam**	**Control**
	100 °C	**100 °C**	**Commercial Parboiled Rice**
T_o	31.00 °C	31.51 °C	31.00 °C
T_P	40.87 °C	41.47 °C	39.57 °C
ΔH	254.4	110.5	263.2

values did not follow the same trend as the crystallinity index calculated from the XRD. The non-steam sample had the highest XRD crystallinity index (72.00%) but the lowest ΔH (110.5 J/g). Commercial parboiled rice had the lowest XRD crystallinity index (19.90%) but the highest ΔH (263.2 J/g).

The present results thus indicate that XRD crystallinity index and DSC gelatinisation enthalpy should not be considered as equivalent measures of starch crystallinity. XRD provides information on the relative crystalline order that is detectable by X-ray diffraction, whereas DSC measures the thermal energy associated with the disruption of thermally detectable starch structures during gelatinisation. The observed differences between the two techniques may be indicative of differences in the structural organization and thermal behaviour of starch after the different processing treatments. The XRD and DSC results thus complement each other to describe the structural and thermal characteristics of the rice samples.



(a) (b)

(c)

Figure 1. Thermogram showing the Onset Temperature (T_o), Peak Temperature (T_P), and Gelatinisation Enthalpy (ΔH): (a) Steam sample at 100°C (b) Non-steam sample at 100°C (c) Commercial parboiled rice

Total Phenolic Content (TPC) and Antioxidant Activity of Parboiled Rice

In this study, rice samples were used for TPC and antioxidant activities to represent rice as commonly consumed. The evaluation of bioactive compounds in cooked rice is important since cooking can change the structure of starch and impact the nutritional quality.

The total phenolic content (TPC) of the selected 100 °C steam-treated and non-steam-treated rice samples and commercial parboiled rice is presented in Figure 2. No significant difference in TPC was observed among the evaluated samples ($p > 0.05$). The results indicate that the steam treatment at 100 °C did not significantly affect the TPC compared with the non-steam treatment at the same drying temperature. The sample treated with superheated steam at 100 °C showed a relatively high phenolic content, similar to the commercial parboiled rice, indicating that steam treatment could enhance the release or preservation of phenolic chemicals in the rice matrix. The presence of moisture during steam treatment increases hydrolytic reactions, leading to the weakening of phenolic-cell wall connections (Gupta & De, 2017; Wu et al., 2018). There was also no significant difference between the steam and non-steam treatments at 100 °C, indicating that this temperature was sufficient to disturb the rice matrix and release bound phenolics but not high enough to cause major breakdown.

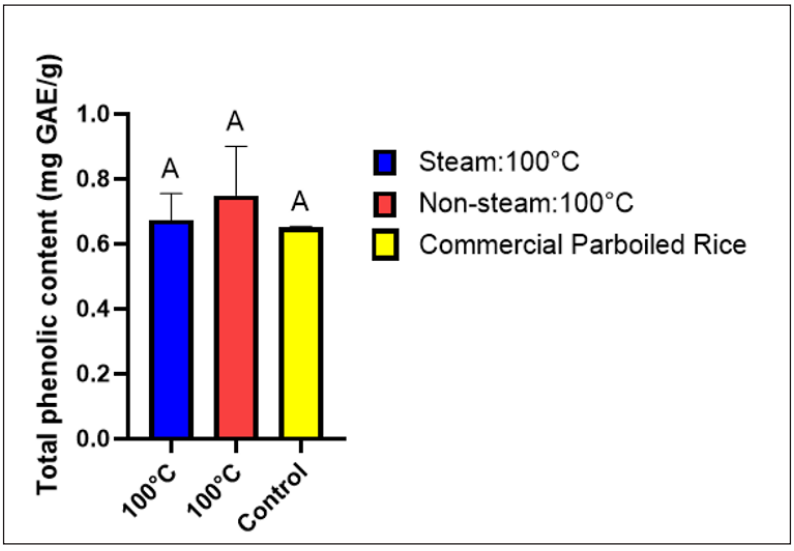


Figure 2. Total phenolic content and antioxidant activity of steam and non-steam rice samples at 100 °C and commercial parboiled rice

In fact, total phenolic content was generally associated with antioxidant activity. No significant difference in antioxidant activity was observed between the steam-treated and non-steam-treated samples at 100 °C ($p > 0.05$). This result was consistent with the TPC

findings, where no significant difference was observed between the two treatments. The relatively similar antioxidant activity may indicate that the 100 °C steam treatment did not significantly alter the antioxidant compounds detectable by the DPPH assay. Phenolic compounds can contribute to antioxidant activity through their ability to scavenge free radicals (Mathew et al., 2015). However, DPPH activity represents the overall radical-scavenging capacity of the extract and may not necessarily correspond directly to the measured TPC.

CONCLUSION

The results concluded that SSD at 100 °C was successful in maintaining rice quality with HRY (90.61%) and starch characteristics (amylose content, 46.80%; crystallinity, 54.25%; gelatinisation enthalpy, $\Delta H = 254.4$ J/g). The bioactive substances, such as TPC (0.67 mg GAE/g) and antioxidant activity (75.7%), had minimal nutritional degradation.

Results also demonstrated a positive correlation between gentle SSD treatment (100 °C) and the preservation of kernel structure, starch crystallinity, and antioxidant activity. At the higher drying temperature of 120 °C, the HRY and amylose content were still relatively high, indicating that the SSD process kept these quality characteristics within the investigated temperature range. The present findings contribute to the current knowledge of superheated steam processing of parboiled rice and provide a basis for further optimisation of SSD conditions to achieve desirable nutritional and textural properties.

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Factors Affecting the Adoption of Climate-Smart Agriculture (CSA) Practices for Sustainable Food Production and Aligned with SDGs in Malaysia

Zeeshan Tariq, Hui-Nee AuYong*, and Abdelhak Senadjki

Teh Hong Piow Faculty of Business and Finance, Universiti Tunku Abdul Rahman,31900 Kampar, Malaysia

ABSTRACT

Ensuring sustainable food production has become a national priority in Malaysia as climate change and environmental pressures increasingly threaten agricultural productivity and resilience. In response, climate-smart agriculture (CSA) has emerged as a strategic approach to strengthening adaptive capacity, improving productivity, and enhancing sustainability in agricultural systems. This study investigates the determinants affecting the adoption of CSA practices among Malaysian agricultural producers and examines their associations for sustainable food production within the Sustainable Development Goals (SDGs) framework. Grounded in the theory of access, the study develops a conceptual framework integrating land availability, trialability and farmers' acceptability as key determinants of CSA adoption, with government support modelled as a moderating variable. A quantitative research methodology was employed, and data were collected from 409 agricultural producers across multiple Malaysian states. The proposed relationships were analysed using partial least squares structural equation modelling (PLS-SEM) through SmartPLS 4.1. The results reveal that land availability significantly influences CSA adoption, while trialability and farmers' acceptability insignificantly influence sustainable food production. Furthermore, CSA adoption positively supports sustainable food production, underscoring its role in enhancing agricultural resilience and food security. Government support for CSA practices for sustainable food production is negligible. Overall, the results provide empirical evidence that primarily encourages agricultural producers and agribusinesses to accelerate the adoption of CSA practices for sustainable food production in Malaysia, aligned specifically with SDG 2 (Zero Hunger) and SDG 13 (Climate Action).

Keywords: CSA practices, farmer's acceptability, government support, land availability, trialability, sustainable food production

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E-mail addresses:
zeeshantariq@1utar.my (Zeeshan Tariq)
auyonghn@utar.edu.my (Hui-Nee AuYong)
abdelhak@utar.edu.my (Abdelhak Senadjki)
* Corresponding author

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INTRODUCTION

A global agricultural commodity is the production of food and other non-food items (Frey & Bruckner, 2021). Every country's agriculture sector plays a significant part in providing its people with economic opportunity and food security (Kumar, 2024). Climate-resilient agricultural diversification, climate-resilient crop varieties, conservation agriculture, water management strategies, integrated pest control and nutrient management are some of the CSA practices used in several Asian countries to enhance agricultural production (Nguyen et al., 2025). However, fruits, vegetables and grains are crucial for ensuring national food security (Dardak, 2021). Malaysia relies on imports of 30 40% from other countries to meet food demand (Tariq et al., 2026). One of Malaysia's biggest challenges in the agriculture area is how agricultural producers implement CSA practices for sustainable food production (SFP) (Aziz et al., 2024). Sustainable food production can be seriously threatened by land constraints, current land instability and limited access to available land. Land availability creates a long-term investment challenge for the implementation of CSA practices (Murken & Gornott, 2022). Access to resources is quite restricted; this study has stated the gap in how agricultural producers may face several problems in the execution of CSA practices to provide sustainable food production (Tariq et al., 2026). The acceptability approach of agriculture producers to adopt CSA practices is still beginning considered. Agriculture producers perceptions of risk and cost are linked together. Opportunities for producing sustainable food make it difficult to fully assess farmers' acceptability of executing CSA practices (Nyang'au et al., 2021). To ensure SFP, the Malaysian government supports the assumption that agricultural output would increase by 53.6%, from 1.51 M tonnes in 2019 to 2.32 M tonnes by 2030, which is quite a big challenge, at a compound annual growth rate (CAGR) of 4.89% (Dorairaj & Govender, 2023). Agriculture remains a fundamental support of Malaysia's socioeconomic development, contributing significantly to the country's livelihoods, national food resources, and economic stability (Mohd Yusoff et al., 2025).

However, the sector is increasingly confronted by difficult challenges arising from climate variability, land-use pressures, environmental degradation and rising food needs (Rahmat & Hamid, 2025). Further, access theory explains agricultural producers' ability to obtain agricultural resources, which can influence the adoption of CSA practices and ultimately meet sustainable food production. Land availability signifies agricultural producers' physical access to productive agricultural land, while trialability signifies their opportunity to experiment with CSA practices before making a larger commitment. Farmers' acceptability signifies their willingness to accept CSA practices within their existing farming systems. These access-related conditions can facilitate or constrain farmers' ability to convert available resources and opportunities into adoption of CSA practices (Tariq et al., 2026). Government support can increase this process by providing financial incentives and extension services that reduce agricultural producers' access constraints (Mutea et

al., 2020). Consequently, greater access to land, opportunities to trial CSA innovations, farmer acceptability and government support can encourage adoption of CSA practices, which can ultimately enhance sustainable food production. This study aims to examine the determinants of CSA adoption among Malaysian agricultural producers, with government support modelled as a moderating variable, and to assess the implications for sustainable food production in alignment with the SDGs.

Literature Review

Sustainable food production is the development of increasing, reaping and distributing food in a way that preserves and improves the environment, supports rural economies and farmer livelihoods and ensures food security (Wang, 2022). Sustainable food production is the progression of cultivating food using socially, economically and environmentally sound techniques so that agriculture can be sustainable and supply food and revenue for forthcoming generations (Çakmakçı et al., 2023). To achieve the Sustainable Development Goals (SDGs), such as SDG 2 (Zero Hunger) and SDG 13 (Climate Action), the food production system needs to be transformed to be more sustainable (Hoek et al., 2021). CSA practices represent a collection of agricultural practices that influence sustainable agricultural production. CSA practices consider the trade-offs and collaborations between productivity, mitigation and adaptation, with a specific focus on tackling climate change in the agricultural sector (Waaswa et al., 2022). Using contemporary agricultural technology and innovations, the primary objective of adopting CSA practices is to establish resilient structures and high agricultural productivity (Muriithi et al., 2023).

Agricultural producers, who fundamentally rely on their land and the right to utilise it, are particularly influenced by land availability (Singirankabo et al., 2022). In the context of climate change, land availability is thought to be crucial for the execution of CSA practices, which are necessary for sustainable food production (Tseng et al., 2021). Before a technology is adopted on a large scale, it must first be tested on a small scale (Valizadeh et al., 2023). Trialability offers an opportunity for experiential learning, allowing agricultural producers to understand how a new technology functions under specific conditions (Kirungi et al., 2023). Agriculture producers are striving toward sustainable food production by executing CSA practices through acceptability approach (Panyasit et al., 2024). Farmers' acceptability reflects their capacity, readiness and willingness to embrace CSA practices and respond favourably to climate change (Belay et al., 2022). CSA practices are more likely to be adopted by agricultural producers who get financial support (Damba et al., 2024). Adoption of CSA practices is also encouraged by peers, and agricultural producers are more open to long-term implementation (Kassa & Abdi, 2022). However, a lack of information, awareness, and training hinders the adoption of CSA practices, which has a detrimental influence on sustainable food production (Karimi & Ataei, 2024).

Theoretical Foundation

This study is grounded in theory which explains the connection between adoption of CSA practices and SFP outcomes. It draws on the theory of access, which posits that agricultural producers adopt CSA practices by accommodating land availability, trialability and farmers' acceptability of SFP (Mgomezulu et al., 2024; Usika et al., 2024). In the context of agricultural production, the three independent variables in this study land availability, trialability and farmers' acceptability function as specific forms of accessibility that can encourage agricultural producers to adopt CSA practices. The dependent variable, sustainable food production, represents the perceived return through CSA practices adoption, while the moderating variable, government support, reflects the idea that the benefits of capital may differ depending on how agricultural producers access facilities and at which level government can encourage the adoption of CSA practices for SFP.

To assess individual preparedness to adopt CSA practices, the study incorporates the access theory developed by Jesse Ribot and Nancy Peluso in 2003. This theory helps explain variation in accessibility of land availability, trialability and farmers' acceptability among agricultural producers. Within this theory, land availability is examined along trialability and farmers' acceptability, recognising that agricultural producers with access are more likely to acquire and effectively use relevant CSA practices, contributing positively to SFP. The moderating role of government support is also relevant here, as access to government support may affect agricultural producers differently due to differences in exposure or regional differences.

Finally, the study builds upon established sustainable food production models proposed by Francisco et al. (2023) and Zhu et al. (2018), which conceptualise SFP as a multi-dimensional construct that encompasses overall value in production. In this context, land availability, trialability and farmers' acceptability align with the adaptive competencies that are highlighted as critical for agricultural production. It has been observed that government support has a moderating effect in this study, which reflects that access to government support for agricultural producers would be helpful for sustainable food production.

Hypothesis and Conceptual Framework

According to land availability, agricultural producers believe they have the right to access, use, and govern all the land. Agricultural producers are inclined to embrace CSA practices because of these factors (Kehinde et al., 2022). H1: Land availability has a significant positive effect on the adoption of CSA practices. Agricultural producers communicate their CSA adoption experiences with their fellow farmers through trialability (Kwapong et al., 2024). H2: Trialability has a significant positive effect on the adoption of CSA practices. CSA practices are further expected to be adopted by agricultural producers who are more aware of the outcomes of climate change. Due to environmental changes,

agricultural producers tend to adopt CSA practices more (Antwi-Agyei et al., 2023). H3: Farmers' acceptability has a significant positive effect on the adoption of CSA practices. By encouraging long-term investments, facilitating access to institutional and financial assistance and creating a solid basis for robust, successful farming systems, land availability benefits SFP (Wang, 2022). H4: Land availability has a significant positive effect on SFP. Agriculture producers are enabled to test new CSA practices on a small scale, lowering risk, boosting confidence and promoting wider adoption, all of which support the shift to more resilient, effective and environmentally friendly agriculture structures in which trialability enhances SFP (Kirungi et al., 2023). H5: Trialability has a significant positive effect on SFP. Agriculture producers' approach toward acceptability is influenced by peer pressure and social learning, which enable them to fulfil SFP targets (Ramborun et al., 2020). H6: farmers' acceptability has a significant positive effect on SFP. To achieve SFP outcomes, CSA practices represent an approach that integrates multiple factors (Aziz et al., 2024). All these factors work together to adopt CSA practices and create SFP in an alternative way. H7: Adoption of CSA practices has a significant positive effect on SFP. Policy, financial, technical, and institutional assistance for sustainable agriculture are important ways the government encourages and facilitates agricultural producers' adoption of CSA techniques (Hussain et al., 2025). H8: Government support has a significant positive effect on SFP.

Mediating & Moderating role in Adoption of CSA Practices

According to recent studies, however, the influence of land availability on SFP is not always direct; rather, it frequently occurs through the implementation of successful CSA methods (Mizik, 2021). In the context of adoption of CSA practices, trialability plays an essential role because CSA practices often involve changes in crop management, soil practices and irrigation systems that agricultural producers may hesitate to adopt without prior testing (Senyange, 2022). A mediated relationship is theoretically supported in which farmers' acceptability increases the likelihood of CSA practices, and adoption of CSA practices enhances SFP (Wang et al., 2025). Agriculture producers are encouraged to adopt CSA methods for SFP by government support through policies, subsidies, technical aid and financial support, as well as ongoing training and development assistance and infrastructure development in general (Aerni & Zou, 2022).

H9a: The adoption of CSA practices mediates the relationship between land availability and SFP.

H9b: The adoption of CSA practices mediates the relationship between trialability and SFP.

H9c: The adoption of CSA practices mediates the relationship between farmers' acceptability and SFP.

H10: Government support moderates the relationship between the adoption of CSA practices and SFP.

Conceptual Framework

The conceptual framework of the current study is built around six key variables and is informed by the theory of access, as shown in Figure 1. To begin with, the capacity to optimise the factors, assess them, and use them effectively is required to be able to contribute to SFP (Movilla-Pateiro et al., 2021). Second, the connection of independent variables to sustainable agriculture production through CSA practices (Agyekum et al., 2024). Thirdly, government support reflects the confidence of agricultural producers in adopting CSA practices (Van Asseldonk et al., 2023). The outcome variable of the study, SFP, represents the perceived ability of agricultural producers to optimise CSA practices (Tay, 2024). In line with the access theory lens, the three factors are viewed as land availability, trialability and farmers' acceptability, which can enhance an agricultural producer's productivity. The theory of access reinforces the role of accessibility of resources in encouraging CSA practices and platform awareness. The model allows comparative analysis of factors between CSA practices and SFP by incorporating a moderating variable, government support. This study highlighted and focused on the adoption of CSA practices and its outcomes on SFP. This outcome is different because access theory indicates that the accessibility of resources different at different regions. This research also confirms this conclusion by stating that the levels of adoption of CSA practices differ among regional agricultural producers (Maspan & Halimoon, 2024; Ng et al., 2025).

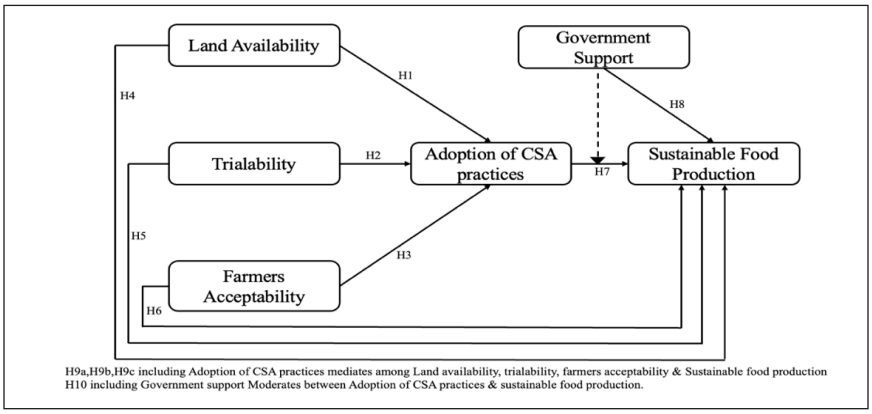


Figure 1. Conceptual framework with direct relationships

MATERIALS AND METHODOLOGY

This study employs a quantitative, cross-sectional study design within a positivist paradigm, which supports objective measurement and statistical analysis. The focus was to investigate the predictive factors of SFP in Malaysia's agriculture sector. Specifically, the study examined the perceptions of agricultural producers regarding the adoption of CSA practices. Approximately one million agricultural producers in Malaysia are involved in agricultural production (Ali et al., 2020). Additional official statistics were obtained from Jabatan Pertanian Malaysia. A non-probability purposive sampling method was used to reach agricultural producers who have been involved in agriculture across Malaysia. This technique was chosen because this study required respondents with specific characteristics; currently employed agricultural producers had an equal opportunity to be selected across Malaysia. Because all variables were self-reported by a single respondent group at a specific moment in time, common method bias (CMB) was assessed. This technique is broadly applied in social sciences when the aim is to gather insights from respondents who can provide the most relevant and informed perspectives on the research questions (Hair et al., 2017). The research has been approved by the relevant ethical committee at UTAR with reference number U/SERC/56(A)-635/2025. Participation was voluntary, and respondents were guaranteed confidentiality and anonymity. Digital knowledge consent was obtained prior to the start of the survey.

Around 650 questionnaires were distributed among agricultural producers, and a total of 409 valid responses were collected, with a 63% response rate, which meets the threshold value of 384 determined by the formula using Krejcie and Morgan's (1970). This sample exceeds the minimum threshold required for further analysis using PLS-SEM (Hair et al., 2017). Data were collected using a structured questionnaire developed based on validated scales adapted from prior studies, as the questionnaire items are presented in Appendix A. A total of four items for SFP have been adopted; four items for the adoption of CSA practices and four items for the trialability scale were adopted to analyse the extent to which agricultural producers are willing to adopt CSA, from Aziz et al., 2024 and Adnan et al., 2020. Four items for land availability were adopted from Hosaena Ghebru & Holden, 2013. Four items for farmers' acceptability were adopted from Masud et al., 2017 and Zulqarnain et al., 2020 and four items for government support were adopted from Bakar et al., 2020, respectively. All the items have been used on a 5-point Likert scale ranging from 1 Strongly Disagree to 5 Strongly Agree. Besides, initially, a pilot test with 30 participants was conducted to ensure the clarity, reliability and face validity of the items. The Cronbach's alpha values for all constructs exceeded the recommended threshold of 0.70, validating internal consistency.

Procedure of Data Analysis

Data have been analysed using SmartPLS 4.1, using a two-stage method, an established PLS-SEM procedure. In the first stage, the measurement model was assessed by investigating internal consistency reliability through Cronbach's alpha and composite reliability, convergent validity using average variance extracted (AVE) and discriminant validity using both the Fornell-Larcker criterion and the Heterotrait-Monotrait (HTMT) ratio. In the second stage, the structural model was assessed to test the hypothesised relationships among variables. This involved analysing path coefficients**,** coefficient of determination (R^2) and predictive relevance (Q^2) values, as well as effect sizes (f^2) to determine the strength of each predictor. Additionally, a moderating analysis was conducted to compare the structural relationships, thereby assessing the moderating effect. This has followed the suggestions of Hair et al. (2020) for strong SEM modelling in social science research and management studies.

RESULTS AND DISCUSSION

This section describes the measurement model validity and reliability while providing the researchers with knowledge on the demographic profile. The summary of respondents' demographic profile is given in Table 1.

Table 1
Summary of demographic profile

		No. of Respondents	Percentage %
Gender	Male	339	83%
	Female	70	17%
Marital Status	Single	218	53%
	Married	191	47%
Ethnic Group	Malay	214	52%
	Chinese	120	29%
	Indian	40	10%
	Others	35	9%
Monthly Income of Farmer	< RM 2000	173	42%
	RM 2001-3000	206	50%
	RM 3001-4000	12	3%
	RM 4001-5000	14	4%
	>RM 5000	4	1%
No. of years of experience	01-5 years	112	27%
	06-10 years	187	46%
	11-15 years	99	24%
	>15 years	11	3%

Table 1 (*continued*)

		No. of Respondents	Percentage %
Location (States) of agricultural producers	1) Kedah	54	13%
	2) Kelantan	49	12%
	3) Selangor	75	18%
	4) Perak	70	17%
	5) Pahang	55	13%
	6) Negeri Sembilan	39	10%
	7) Johor	31	8%
	8) Malacca	8	2%
	9) Perlis	5	1%
	10) Terengganu	7	2%
	11) Sabah	3	1%
	12) Sarawak	4	1%
	13) Penang	9	2%

Table 2
Reliability and convergent validity of constructs

Construct	Alpha	CR	AVE
Adoption of CSA Practices	0.86	0.90	0.70
Farmer's Acceptability	0.88	0.92	0.74
Govt. Support	0.81	0.87	0.63
Land Availability	0.87	0.91	0.72
Sustainable Food Production	0.79	0.86	0.61
Trialability	0.84	0.89	0.68

Table 2 shows that all constructs demonstrate acceptable internal consistency and convergent validity. Cronbach's alpha values exceed the recommended 0.70 threshold, while composite reliability (CR) values range from 0.86 to 0.92, indicating high reliability (Hair et al., 2017). Additionally, average variance extracted (AVE) values for all constructs are above 0.50, confirming convergent validity.

Table 3 shows that discriminant validity has been further assessed using the Heterotrait-Monotrait (HTMT) ratio. All HTMT values ranged below the conservative threshold of 0.90 (Henseler et al., 2015), thereby confirming discriminant validity among all latent constructs.

Further, Table 4 presents the Fornell-Larcker criteria used to evaluate discriminant validity as well. The square roots of the AVEs (diagonal values) meet the threshold value of 0.85, and each construct is greater than its corresponding inter-construct correlations, indicating adequate discriminant validity (Fornell & Larcker, 1981).

Table 5 shows the model's explanatory and predictive capability. The R^2 value for SFP is 0.40, indicating that the predictors explain a moderate amount of variance. The

Table 3
Discriminant validity-Heterotrait-monotrait ratio (HTMT)

	Adoption of CSA Practices	Farmer's Acceptability	Govt. Support	Land Availability	SFP	Trialability
Adoption of CSA Practices	0.33					
Farmer's Acceptability	0.17	0.40				
Govt. Support	0.26	0.32	0.19			
Land Availability	0.48	0.22	0.18	0.64		
SFP	0.51	0.22	0.25	0.20	0.16	
Trialability	0.16	0.03	0.03	0.05	0.14	0.08

Table 4
Discriminant Validity - Fornell-Larcker Criterion

	Adoption of CSA Practices	Farmer's Acceptability	Govt. Support	Land Availability	SFP	Trialability
Adoption of CSA Practices	0.84					
Farmer's Acceptability	0.29	0.86				
Govt. Support	0.15	0.34	0.80			
Land Availability	0.23	0.29	0.17	0.85		
SFP	0.40	0.19	0.16	0.55	0.78	
Trialability	0.44	0.18	0.21	0.17	0.14	0.83

Table 5
R^2, Q^2, and Effect Size (f^2) of the structural model

Construct/ Path	R^2	Q^2	f^2	Effect Size
SFP	0.40	0.28		
Land Availability → SFP			0.02	Small Effect
Trialability → SFP			0.19	Medium Effect
Farmer's acceptability → SFP			0.04	Small Effect

Q^2 value of 0.28 confirms medium predictive relevance. Effect size (f^2) analysis displays that trialability has the largest predictive effect ($f^2 = 0.19$, medium), followed by land availability ($f^2 = 0.02$, small) and farmers' acceptability ($f^2 = 0.04$, small), supporting the relative importance of these predictors within the model.

Table 6 presents the results; the significant result of H1 (β - value = 0.11 and p-value = 0.015). This result indicates that agricultural producers with greater access to suitable and secure agricultural land are more likely to adopt CSA practices. According

Table 6
Structural model assessment, direct effects

H	Relationships	β - value	t-value	p-value	Result
H1	Land Availability -> Adoption of CSA Practices	0.11	2.42	0.015	Supported
H2	Trialability -> Adoption of CSA Practices	0.39	8.36	0.000	Supported
H3	Farmer's Acceptability -> Adoption of CSA Practices	0.19	3.96	0.000	Supported
H4	Land Availability -> SFP	0.53	11.79	0.000	Supported
H5	Trialability -> SFP	0.03	0.57	0.569	Not Supported
H6	Farmer's Acceptability -> SFP	0.01	0.25	0.802	Not Supported
H7	Adoption of CSA Practices -> SFP	0.33	6.86	0.000	Supported
H8	Govt. Support -> SFP	0.07	1.81	0.070	Not Supported

to the theory of access, sufficient land access is generally better positioned to justify investments in improved irrigation systems, soil conservation measures, mechanisation, and digital agricultural technologies because of the expected greater outcome. Consequently, land availability increases both the opportunity and the capacity to implement CSA practices effectively (Myers & Hansen, 2020). The outcomes support a growing body of empirical literature indicating that land availability is a critical determinant of CSA adoption (Ngoma et al., 2021). Second, the results confirm the significance of H2 (β - value = 0.39 and p-value = 0.000). This result suggests that agricultural producers who retain more agricultural trialability opportunities and further acquire knowledge when applying it are more likely to adopt CSA practices. Trialability is a critical mechanism for equipping agricultural producers with the knowledge, technical skills and confidence required to implement CSA practices, ultimately contributing to more resilient and sustainable agricultural systems in Malaysia. The theory of access claims that trialability access mechanisms are interconnected. Trialability enhances agricultural producers' ability to benefit from other productive resources (Peluso & Ribot, 2020). This explains why agricultural producers with higher levels of trialability demonstrate greater adoption of CSA practices. Consequently, trialability supports agricultural producers' ability to benefit from CSA practices (Suresh et al., 2025).

Third, the results confirm the significance of H3 (β - value = 0.19 and p-value = 0.000). This shows that agriculture producers who recognise CSA practices as beneficial are more likely to adopt them. Acceptance behaviour is a critical determinant of CSA adoption and reinforces the importance of promoting favourable perceptions towards CSA practices among Malaysian agriculture producers (Antwi-Agyei et al., 2023). The theory of access also highlights that access mechanisms operate collectively. Consequently, agricultural producers' willingness behaviour is an important pathway which leads to the execution of CSA practices (Khatun et al., 2020). Fourth, the results confirm the significance of H4 (β

- value = 0.53 and p-value = 0.000). This result suggests that agricultural producers with greater access to secure land are more capable of achieving sustainable food production. Land availability remains one of the most fundamental agricultural resources. The theory of access further argues that access mechanisms interact with one another. Land availability enhances the effectiveness of other productive resources because farmers are more willing to invest when they have adequate land resources (Myers & Hansen, 2020). Therefore, the significant relationship observed in this study confirms that land availability serves as a foundational resource that enables agricultural producers to convert other forms of access into sustainable agricultural outcomes (Wang, 2022).

Fifth, the results confirm the insignificance of H5 (β - value = 0.03 and p-value = 0.569). The results show there is an insignificant association between trialability and SFP. As trialability has been widely recognised as an important determinant of innovation adoption, the present findings suggest that the opportunity to experiment with CSA practices is insufficient to improve sustainable food production among Malaysian agricultural producers. Access to providing agricultural producers with opportunities to trial CSA practices does not ensure meaningful expected outcomes (Autio et al., 2021). Agricultural producers may participate in demonstration pilot projects, yet still lack complementary resources such as financial capital, technical knowledge, technology, irrigation facilities, extension services and market access necessary to convert trial experiences into sustainable developments in agricultural productivity (Davis et al., 2021). Trialability provides only initial exposure to innovation rather than the actual capability to achieve sustainable food production.

Sixth, the results confirm the insignificance of H6 (β - value = 0.01 and p-value = 0.802). The results show there is an insignificant association between farmers' acceptability and SFP, indicating that farmers' acceptability is insufficient to produce sustainable production outcomes without actual implementation and access to complementary resources. According to the theory of access, agriculture producers must also possess other factors, including access to financial resources, agricultural inputs, extension services, technology, market opportunities and infrastructure, before acceptability attitudes can be converted into improved food production (Rust et al., 2022). Therefore, while agriculture producers may readily accept CSA innovations, they may still lack the practical means to implement these practices effectively and consistently. Consequently, agriculture producers are deficient in irrigation facilities, machinery, technical training, or affordable financing and may remain unable to achieve sustainable production (Thottadi & Singh, 2024). This explains why farmers' acceptability alone did not significantly predict sustainable food production.

Seventh, the results confirm the significance of H7 (β - value = 0.33 and p-value = 0.000). The results endorse that CSA practices ensure long-term food security while maintaining environmental sustainability, particularly in the Malaysian agricultural

sector. The theory of access further emphasises that multiple access mechanisms operate simultaneously (Peluso & Ribot, 2020). CSA practices serve as the operational pathway that enables agricultural producers to transform diverse forms of access into improved agricultural performance. This theoretical explanation supports that CSA practices contribute to sustainable food production (Ma & Rahut, 2024). Eighth, the results confirm the insignificance of H8 (β - value = 0.07 and p-value = 0.070). This result suggests that government support does not directly improve sustainable food production. The theory of access highlights that institutional mechanisms are insufficient to generate positive outcomes because agricultural producers' ability depends on different factors, including capital, land, technology, labour, knowledge, markets, and social networks (Mutea et al., 2020). In addition, governmental procedures, delays in subsidy distribution and differences in agricultural producers' participation levels may reduce the practical efficiency of government support (Gupta et al., 2023). Consequently, government support may create opportunities for agricultural improvement, but sustainable food production will increase only when agricultural producers have the capacity to combine government assistance with these complementary resources.

Table 7
Structural model results, mediation effects (VAF)

H	Relationships	Formula Outcome	Decision
H9a	Land availability -> Adoption of CSA Practices -> SFP	0.40	Partial mediation
H9b	Trialability -> Adoption of CSA Practices -> SFP	0.83	Full mediation
H9c	Farmer's acceptability -> Adoption of CSA Practices -> SFP	0.85	Full mediation

Further, Table 7 shows indirect mediation effects (VAF), in which H9a = 40% mediation result shows there is partial mediation observed, as land availability is not playing any major role directly in CSA adoption for SFP, can be considered (Bwalya et al., 2023). Further, land availability does not affect the relationship between CSA practices and SFP (Zerssa et al., 2021). In H9b, = 83 % result shows that trialability, as a full mediator between adoption of CSA practices and SFP, can be considered (Teklu et al., 2023). Without trialability, SFP cannot be attained as a mediator between adoption of CSA practices and SFP (Obabire & Adeleye, 2024). In H9c, = 85 % result shows that farmers' acceptability as a full mediator between adoption of CSA practices and SFP can be considered (Antwi-Agyei et al., 2023). Agricultural farmers do not show direct interest in adopting CSA practices at an advanced level for SFP (Gemtou et al., 2024).

Table 8 shows the analysis to assess the moderating role of government support. This result suggests that many Malaysian agricultural producers may not be receiving sufficient or effective support to meaningfully predict their adoption of CSA practices and

Table 8
Structural model results, moderation analysis

H	Relationships	β - value	t-value	p-value	Moderation
H10	Govt. Support x Adoption of CSA Practices -> Sustainable Food Production	0.06	1.639	0.101	Not Supported

subsequent food production outcomes (Sardar et al., 2021). In the Malaysian context, this insignificant relationship is explained by the limited accessibility and implementation gaps of agricultural support programs. While the government has hosted various agricultural modernisation plans through agencies such as the Ministry of Agriculture and Food Security, many agricultural producers continue to experience challenges in accessing subsidies, financial assistance, training and technical knowledge associated with CSA execution (Suffian & Suffian,2023). CSA practices that sustainably increase production resilience to climate change and reduce greenhouse gas emissions are significant to achieving SDG 2 (Zero Hunger) and SDG 13 (Climate Action). CSA practices and SDGs show links: CSA enhances SDG 2 targets on sustainable food production and smallholder productivity, while advancing SDG 13 targets on adaptation and mitigation (Naveen et al., 2024). Zero hunger and climate change are real challenges. SDG 2 encourages ending hunger, and SDG 13 encourages support for resilience to climate change (Naik et al., 2025). The finding may reflect regional differences in agricultural assistance across Malaysian states, where access to infrastructure, extension officers, agricultural programs and institutional resources differs significantly. Agriculture producers in developed agricultural regions may have relatively superior exposure to innovation programs, whereas those in less developed areas may encounter institutional barriers that reduce the efficiency of government support. Such differences may contribute to inconsistent results, an overall statistically insignificant moderating relationship.

CONCLUSION

This research examines variables such as land availability, trialability and farmers' acceptability that affect the application of CSA practices and their consequences for SFP in the context of Malaysia. However, the institutional obstacles small-scale agricultural producers face underscore the need for specialised training initiatives. These findings, which emphasise Malaysia-specific challenges while pointing to general drivers of CSA adoption, are in line with research from throughout the globe. As there are supported hypotheses of H1, H2, H3, H4, H7 and unsupported hypotheses of H5, H6, H8, which stated the significant and nonsignificant relationships among them, respectively. Nonetheless, an intriguing discovery showed that acceptability had a predictive effect on CSA practice adoption. This finding is encouraging because it has suggested that although agricultural producers are

aware of the benefits of using CSA practices for food security, the significant influence of CSA practices on SFP, which aligns with SDG objectives, demonstrates how CSA activities contribute to SFP, considering benefits as well. These results demonstrate that agricultural producers are aware of the potential of CSA practices to encourage sustainable productivity and food security at an advanced level.

THEORETICAL CONTRIBUTIONS

The theory of access provides insights into how access to information, resources and institutional support enables agricultural producers' readiness behaviour to adopt new CSA practices. The pattern of these perceptions conveys a complete understanding of sustainable agricultural adoption in the context of Malaysia. Practically, this study contributes valuable implications for agricultural stakeholders and policymakers by highlighting the necessity for critical interventions that advance agricultural producers' approach to land availability, trialability and farmers' acceptability. Supportive agricultural extension capabilities and increasing awareness of CSA advantages can additionally support adoption among agricultural producers. Moreover, policy frameworks would highlight comprehensive and sustainable agricultural development methodologies which support national food security plans and SDG goals, specifically SDG 2 (Zero Hunger) and SDG 13 (Climate Action).

IMPLICATION OF STUDY

Overall, this study demonstrates that resources alone do not ensure sustainable food production. Alongside theory, productive resources such as land availability, tractability, and government support create value only when agricultural producers have the capability to transform them into effective CSA practices. This study establishes that adoption of CSA practices serves as a critical instrument for sustainable food production by shaping resource efficiency, enhancing agricultural productivity, strengthening climate resilience and supporting food security in Malaysia. The results highlight that trialability, farmers' acceptability of sustainable food production and government support remain insufficient in easing CSA adoption and support its potential for sustainable food production. This emphasises the importance of collective efforts among policymakers, agricultural institutions, extension officers and agriculture producers to accelerate the transition toward CSA practices. The findings therefore suggested that Malaysia should move towards a more integrated approach that combines secure access to productive resources, technology transfer, digital agriculture, and collaboration. This will increase CSA adoption, strengthen climate resilience, improve sustainable food production, and enhance national food security.

LIMITATION AND RECOMMENDATION FOR FUTURE RESEARCH

Despite its contributions, current research recognises various limitations, including contextual and methodological limitations that may limit generalizability. Future research is encouraged to employ longitudinal plans, mixed-method methodologies, or comparative investigations across regions to improve the long-term effectiveness of climate-smart agriculture practices in improving SFP. This study included limited respondents from East Malaysia. Because a single respondent group self-reported at one moment in time, the connections may have been overstated because of CMB. Further research may also investigate mediating and moderating variables, such as climate risk perception, institutional trust and market convenience, to develop understanding of CSA adoption behaviour. In conclusion, climate-smart agriculture represents a sustainable and strategic path to help Malaysia's food production systems. By focusing on strategic adoption determinants and enhancing institutional support, CSA practices can significantly contribute to sustainable food security, resilient agriculture and the broader achievement of the SDG goals, specifically SDG 2 (Zero Hunger) and SDG 13 (Climate Action), in Malaysia.

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APPENDIX (A)

Questionnaire Items
Sustainable Food Production
I believe CSA practices will ensure sufficient sustainable food production.
I believe that CSA practices enhance sustainable food production by promoting resilience to climate change.
I believe CSA practices will reduce disease outbreaks agriculture production.
I believe CSA practices can produce high-quality food output.
Adoption of Climate Smart Agriculture (CSA) Practices
I believe that adopting CSA practices benefits agricultural production while preserving the environment.
I ensure that water resources are efficiently utilized when adopting CSA practices.
I am using CSA practices to protect the agriculture production from impact of climate change.
I am willing to promote the advantages of CSA adoption for agriculture growth to peers.
Land Availability
I believe land availability give me confidence to invest in CSA practices.
I believe having a land availability certificate increases chances of incentives from Government.
I believe a land certificate can reduces inheritance-related disputes.
I believe having a land availability certificate enhances the access to credit for investing CSA practices.
Trialability
There are agencies that allow farmers to try out CSA practices before adopting.
I would be more inclined to adopt CSA practices if I had the chance to test them first.
I will be more confident in adopting CSA practices if initial trial opportunities are provided.
I believe CSA practices are easy to test on small scale before full adoption.
Farmer's Acceptability
I feel acceptability is become necessary for all of us.
I believe the adoption of CSA practices can guarantee the quality and quantity of farm production.
I believe the adoption of technology can increase agriculture production.
To me, technology is needed.

Questionnaire Items
Government Support
I am aware of government support which promote CSA practices.
I believe Government subsidies can reduce the risk in adoption CSA practices.
I believe government policies providing helpful information about CSA practices.
I believe that government help agricultural producer in accessing input needed for CSA practices.

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Nutrient Release Behaviour of POME-Derived Organo-Mineral Fertilisers in Acidic Ultisol

Fadeila Mohamed Hashim Ali, Syaharudin Zaibon*, and Susilawati Kasim

Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia(UPM), 43400 Serdang, Selangor, Malaysia

ABSTRACT

This study investigated the nutrient release behaviour of organic and organo-mineral fertilisers made from palm oil mill effluent (POME) in an acidic Ultisol under regulated incubation. The experiment used a completely randomised design with eight treatments and 400 g of soil, incubated for 60 days at 25 °C. The treatments comprised soil only, mineral fertiliser, POME only (one formulation), and blends of POME and minerals (two formulations). The first Ultisol was strongly acidic (pH 4.46), low in cation exchange capacity (10.16 cmol (+) kg^{-1}), and severely deficient in available phosphorus (P), calcium (Ca), magnesium (Mg), and potassium (K), while POME sludge was indicative of nutrient contribution potential. The study showed that the fertilised treatments had significant improvement in the soil pH and nutrients. In terms of short-term nutrient release (particularly phosphorus and several base cations), treatment T3 (120% POME) produced the best results, suggesting that POME sludge has a high nutrient-supply capacity. However, T5 (80% POME + 20% mineral fertiliser) exhibited the most balanced, slow nutrient-release pattern throughout the incubation. Further, T5 also managed to moderate soil pH better than the single-source treatment. The results show that organo-mineral fertiliser based on POME could improve nutrient availability in acidic tropical soil. It could reduce the reliance on synthetic fertiliser. Furthermore, it offers a more sustainable nutrient management strategy in low-fertility Ultisol systems with practical value for sustainable recycling of agro-waste.

Keywords: Agricultural waste, incubation, palm oil mill effluent, sustainable agriculture, weathered soil

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E-mail addresses:
alifadeila69@gmail.com (Fadeila Mohamed Hashim Ali)
syaharudin@upm.edu.my (Syaharudin Zaibon)
susilawati@upm.edu.my (Susilawati Kasim)
*Corresponding author

INTRODUCTION

Nutrient management is a critical issue in tropical agriculture. Indeed, in highly weathered soils, crop productivity depends not just on fertiliser input, but importantly

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on the efficiency of nutrient retention and release in the soil system. According to the Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture (USDA) (n.d.) and the University of Idaho (n.d.), Ultisols are strongly weathered soils that are usually acidic, low in base saturation, and naturally limited in nutrient availability. According to Burbano et al. (2022), acidic tropical soils that occur in Malaysia, such as Ultisols and Oxisols, often need amendments to enhance their fertility and sustain crop production. It is vital to note that low pH, weak nutrient-holding capacity, and limited exchangeable bases reduce fertiliser efficiency and can limit the response, even when nutrients are added.

The problem that arises is not only low fertility but also low nutrient use efficiency. In Ultisols, which have an acidic nature, phosphorus is fixed easily, while nitrogen and potassium are less efficiently absorbed because the soil is not able to hold nutrients strongly enough. The works of Dermiyati et al. (2016) and Fahrunsyah et al. (2019) can be used to identify several soil components in Ultisols that can improve plant growth and phosphorus uptake. Various improvements with fertilisers and other nutrients can improve Ultisol growth factors. The findings imply that fertiliser strategies in acidic soils should focus not only on application rate but also on nutrient release behaviour, nutrient retention, and improvements in soil chemistry.

However, excessive use of mineral fertilisers raises agronomic and environmental problems at this time. According to Ditta and Arshad (2016), modern fertiliser management should transform into efficient and sustainable nutrient delivery systems. Further, Nongbet et al. (2022) highlighted that modern agricultural research is emphasising intelligent fertilisers that reduce losses and optimise synchrony between nutrient release and crop demand. Uddin et al. (2025) mentioned that organo-mineral fertilisers are gaining importance these days as their use can maintain soil health and yield, besides having a lesser environmental burden than the use of chemical fertilisers. For this reason, there is strong justification for the search for alternative fertiliser systems that can perform better in acidic tropical soils.

One possible resource is palm oil mill effluent or POME. This is produced in large quantities while palm oil is produced and is considered to be a waste management problem. However, recent studies have shifted views on POME sludge as a viable agrochemical. As reported by Mohd Nizar et al. (2018), application of treated POME sludge enhanced growth performance and gas exchange of maize. This indicated that POME sludge contributes useful nutrients to the crop system. According to Mutar et al. (2025), POME sludge could be used as a reusable source of micronutrients and other beneficial elements. Furthermore, palm oil mill waste could be better converted into useful products instead of being left as waste (Nagime et al., 2025).

POME's role in sustainable agriculture is further accentuated when used as organo-mineral fertilisers. Organo-mineral fertilisers involve adding organic material to a mineral

nutrient source to provide a high initial nutrient supply and gradual nutrient release. According to Moreira et al. (2021), the chemical soil properties can be modified with the use of pelletized organo-mineral fertilisers, while Gonçalves et al. (2021) state that the use of organo-mineral fertilisers based on waste-derived organic sources improved important chemical and technological properties in agricultural crop production systems.

According to Hawrot-Paw et al. (2022), the organo-mineral fertiliser derived from sewage sludge affects both soil biological quality and crops' physiological performance. All in all, these studies suggest that waste-derived organo-mineral fertilisers may become useful instruments for nutrient recycling, enhancing soil quality, and sustainable crop production.

Despite the growing interest, little is known about the nutrient release behaviour of POME-derived fertiliser in acidic Ultisol. Many studies have focused on crop response, soil improvement or the overall promise of organic amendments. But pure mineral fertiliser, pure POME-based fertiliser and blended organo-mineral formulations and their differences in releasing nutrients over time under controlled acidic soils are less explored. The possibility of a deficient or excess supply of a needed nutrient in soil can also arise due to fertilisers and their marginal efficiency. According to Uddin et al. (2025), organo-minerals offer practical value in aiding the fast availability of nutrients with a slow release and lower environmental losses.

Soils that have high acidity and limited nutrient-holding capacity face a problem of serious concern. Nutrients being released too fast means that part of the fertiliser you applied may either get lost or become less available. When release is too slow, crops may miss out on sufficient nutrients at the time they need to be at their maximum. POME sludge cannot be utilised directly to provide nutrients for the plants. However, its mineral and organic nutrients can be made available through formulations. Pure mineral, pure organic, or blended organo-mineral formulations need to be directly compared to determine which formulation provides the best nutrient release pattern in the soil, which is acidic and tropical. The comparison is necessary to progress from blanket statements about organic recycling to more specific fertiliser design evidence.

Consequently, this study assessed the nutrient-release behaviour of mineral-, organic-, and organo-mineral POME-based fertiliser formulations in an acidic Ultisol under incubation-controlled conditions. It examined changes in soil pH and the release of major nutrients from the three fertiliser formulations over time to identify formulations that release nutrients more balanced and sustainably.

This research will contribute to the development of sustainable fertiliser for acidic tropical soils. The study has focused on nutrient release behaviour rather than total nutrient composition. It helps formulate a more realistic basis for the design of fertilisers related to soil constraints and nutrient release behaviour. This aligns with the general trend of sustainable nutrient management identified by Ditta and Arshad (2016), Nongbet et al.

(2022), and Uddin et al. (2025), all of whom emphasise the need for fertiliser systems that would enhance efficiency and minimise environmental footprint.

Furthermore, the findings lend support to the transformation of POME from an agricultural waste nuisance into a fertiliser resource. Given that the palm oil businesses produce a lot of waste streams, the addition of POME sludge will give a more circular and sustainable alternative to dependence on completely synthetic fertilisers. In this sense, the study is relevant not only to soil fertility management but also to waste reutilisation and sustainable agricultural production. For the acidic Ultisols that have persistently low pH, poor phosphorus availability and weak base status as limitations, successful POME-based organo-mineral fertiliser application may help improve phosphate availability and reduce dependence on conventional mineral fertiliser. This research paper is organised with a thoughtful structure. First, the introduction is covered in Section 1. Then, Section 2 discusses the materials and methods. After that, Section 3 covers results and discussion. Finally, Section 4 is the conclusion.

MATERIALS AND METHODS

This study used the laboratory incubation method to determine the nutrient release behaviour of POME organic and organo-mineral fertilisers in acidic Ultisol. First, relevant materials were collected at the local level and standardized for laboratory evaluation. The Ultisol used in the study was collected from the Farm of University Putra Malaysia (UPM), while the organic material used was POME sludge obtained from the open treatment ponds at a palm oil mill. Table 1 summarises the main materials, sampling sources, and scope of preparation.

Table 1
Study materials

Item	Description
Soil material	Bungor series soil (Ultisol) collected from UPM faculty farm. Ladang 16 at 16°58′48.1″ N, 10°43′45.7″ E
POME material	POME sludge collected from Palm Oil Mill at Felda Jengka 8, Bandar Tun Abdul Razak Jengka, 26400 Jengka, Pahang, Malaysia
Soil sampling depth	0-20 cm topsoil
Soil sampling tools	Stainless-steel auger; stainless-steel core ring (7.6 cm x 4 cm); hammer
POME source	Open treatment ponds
Initial sample handling	Samples placed in clean containers, labelled, and transported to the laboratory
Standard preparation	Air-drying, grinding/milling, and sieving to 2 mm
Purpose of preparation	To obtain uniform laboratory material for physical, chemical, and formulation analyses

Soil samples were collected from the 0-20 cm layer using a stainless-steel auger and undisturbed core samples using a stainless-steel core ring (7.6 cm × 4 cm) with a hammer wherever required for physical analysis. Once collected, all samples were placed in clean containers, labelled appropriately, and delivered to the laboratory. After that, the soil and POME sludge were air-dried, milled, and sieved through a 2 mm sieve for analysis and formulation. The incubation medium, an acidic Ultisol, initially had a pH of approximately 4.8. To determine nutrient contribution potential and major fertility constraints after fertiliser formulation, baseline characterisation was undertaken to measure the main physical and chemical properties of the soil and the chemical properties of the POME sludge. The analytical methods applied in this stage are stated in Table 2.

Table 2
Analytical methods

Parameter	Method / Instrument	Purpose
Particle-size distribution	Pipette method	Baseline physical characterisation
Bulk density	Core ring method	Baseline physical characterisation
Moisture retention	Pressure Plate Chamber method	Water retention-related indices
Soil pH	pH meter	Soil acidity assessment
Electrical conductivity (EC)	EC meter	Salinity / soluble ion status
Total N	Kjeldahl digestion block	Nitrogen determination
Available nutrients	Spectrophotometer	Colorimetric nutrient determination
K, Ca, Mg	Atomic Absorption Spectrometer (AAS)	Cation concentration measurement
CEC	Ammonium acetate at pH 7(1945).	Soil fertility and nutrient-holding capacity
POME sludge chemistry	Dry ashing	Nutrient contribution for OMF formulation

An analysis of various soil characteristics from the respective sites was undertaken. Physical analysis included soil texture, bulk density, and moisture retention. Chemical analysis included soil pH, electrical conductivity, total nitrogen, selected available nutrients, cation concentrations and cation exchange capacity. Soil pH was measured using a pH meter. Electrical conductivity was determined using an EC meter, and total nitrogen was analysed by Kjeldahl digestion block. Using a spectrophotometer, available nutrients were determined. K, Ca, and Mg cations were determined by Atomic Absorption Spectrophotometer (AAS). The cation exchange capacity (CEC) was determined using ammonium acetate at pH 7. For the POME sludge, the dry ashing method was used to analyse calcium, magnesium, phosphorus, and potassium. Nitrogen was analysed using the Kjeldahl method.

The fertiliser materials underwent preparation for formulation after baseline characterisation. According to a target formulation of 15:15:15:3:2. T2 mineral fertiliser made out of ammonium sulphate, phosphate rock, muriate of potash (MOP) and dolomite, with a nutrient rate basis of 120:60:90 kg ha^{-1} at 400 kg ha^{-1}, was used. The organic component was air-dried POME sludge, which was milled and sieved with 2 mm mesh to enhance uniformity during mixing. The binder was clay at a controlled rate of 10%, resulting in a base organic mixture of 90% POME sludge and 10% clay. According to the incubation study, this ratio was chosen to optimise pellet integrity and handling. Prior to mixing, all materials were checked for sufficient dryness and clumping. Each batch of raw materials and prepared materials was labelled properly.



Figure 1. Mixing and batching procedure for the preparation of mineral and POME-based organo-mineral fertiliser

As depicted in Figure 1, mixing and batching of the POME and clay binder were carried out according to the fixed 90:10 base ratio as shown in Table 3. The required quantity of both the POME sludge and clay binder was weighed for each formulation first. This was followed by weighing the calculated amounts of ammonium sulphate, phosphate rock, MOP and dolomite. Distilled water was then added little by little and blended on an electric mixer until a homogeneous colour and texture were formed with no visible dry pockets and adequate binding capacity for the formation of pellets. To reduce cross-treatment contamination, each batch was prepared separately and labelled upon mixing. Weighing in at one-half to three-quarters of an inch in diameter, the finished materials can either be pelletised or granulated for ease in fertilizer handling and application.

The completely randomised design of the incubation experiment had eight treatments, each applied to 400 g of acidic Ultisol and incubated for 60 days at 25 °C. Table 3 provides information on the treatment structure, which consisted of T1: soil only (control), T2: 100% mineral fertiliser (Recommendation fertiliser), T3: 120% POME, T4: 100% POME, T5: 80% POME + 20% mineral fertiliser, T6: 60% POME + 40% mineral fertiliser, T7: 40% POME + 60% mineral fertiliser, and T8: 20% POME + 80% mineral fertiliser. Following wet mixing, the homogenised materials were fed into a mill to produce pellets, and the pellets obtained for each treatment were separately collected and labelled. The pellets were oven-dried at 56 °C and then kept at room temperature for 48 hours to improve stability. All pellets were dried under the same conditions and checked to ensure they remained dry and

Table 3
Treatment layout

Treatment	Composition	Description
T1	Soil	Control 1
T2	100% mineral fertiliser	Control 2
T3	120% POME	Organic treatment
T4	100% POME	Organic treatment
T5	80% POME + 20% mineral fertiliser	Organo-mineral treatment
T6	60% POME + 40% mineral fertiliser	Organo-mineral treatment
T7	40% POME + 60% mineral fertiliser	Organo-mineral treatment
T8	20% POME + 80% mineral fertiliser	Organo-mineral treatment

stable without cracking or softening during handling. The final pellets were standardised to a diameter of about 0.5 cm and a length of 2.5 cm for application.

All treatments were maintained under similar laboratory conditions during incubation. The same acidic Ultisol source was used with the same application basis for comparability. According to the 15:15:15 fertiliser reference, the application rate for all treatments in the experiment was 400 kg ha^{-1}, or approximately 2 g per container. Each week, soil or leachate extracts were collected, filtered before instrumental analysis, and analysed for NH_4+ (ammonium), NO_3 − (nitrate), available P, available K, available Ca, and available Mg. To allow comparisons of trends in nutrient release from week to week across T1-T8, all data were systematically recorded by treatment, replicate, and week. This dataset was subsequently used to assess the nutrient-release behaviour of mineral, organic, and organo-mineral fertilisers, and to identify formulations with greater potential for sustained nutrient availability.

RESULTS AND DISCUSSION

It is well known that palm oil mill effluent can alleviate nutrient deficiencies in poor Ultisols. As shown in Table 4, it has a very high potential to contribute nutrients. As far as the Ultisol condition is considered, it is strongly acidic with a pH of 4.46. Furthermore, it has extremely low available P of 0.057% (Bray-1), a cation exchange capacity of 10.16 cmol(+) kg^{-1}, as well as very low exchangeable Ca, Mg and K. Moreover, it is noted that the Ultisol is very low in nutrient content.

Similarly, it is strongly acidic but less so than Ultisol, with a pH of 5.6. Above all, it is very high in nutrient content, which is extremely beneficial in minimising deficiencies in Ultisol. Here is the tabulation of the contents of the study. In view of this, the fertilised treatments clearly affected soil acidity and nutrient release more than the control.

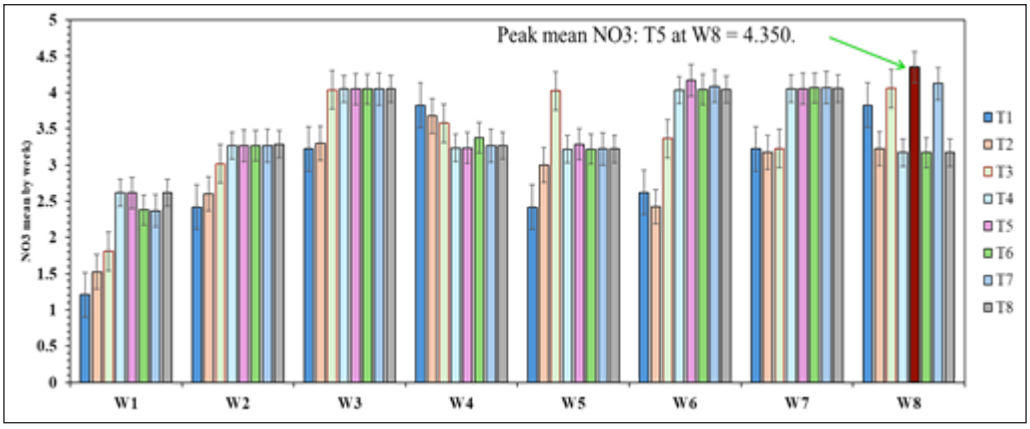
Table 4
Baseline properties of the acidic Ultisol and nutrient composition of POME sludge

Material	Parameter	Unit	Value	Interpretation
Acidic Ultisol	pH (H_2O, 1:2.5)	-	4.46	Strongly acidic soil condition
Acidic Ultisol	Organic carbon	%	1.79	Low organic-C signal in the baseline sample
Acidic Ultisol	Total N	%	0.24	Medium N status
Acidic Ultisol	Total P	%	0.057	Very low and limiting
Acidic Ultisol	CEC	cmol(+) kg^{-1}	10.16	Low nutrient-holding capacity
Acidic Ultisol	Exchangeable Ca^{2+}	cmol(+) kg^{-1}	0.075	Very low
Acidic Ultisol	Exchangeable Mg^{2+}	cmol(+) kg^{-1}	0.082	Low
Acidic Ultisol	Exchangeable K^{+}	cmol(+) kg^{-1}	0.1435	Very low
Acidic Ultisol	Texture	-	Clayey	High clay fraction affecting water and nutrient dynamics
POME sludge	pH	-	5.6	Mildly acidic and less acidic than the soil
POME sludge	Total N	%	2.30	High N contribution potential
POME sludge	Total P	%	0.46	Strong P reserve for nutrient balancing
POME sludge	Organic carbon	%	9.40	High organic-C. signal in the POME sample
POME sludge	K	%	0.64	Meaningful K contribution
POME sludge	Mg	%	0.65	Supports Mg supplementation
POME sludge	Ca	%	3.09	Strong Ca input for low-Ca Ultisol
POME sludge	Humic acid	%	0.64	

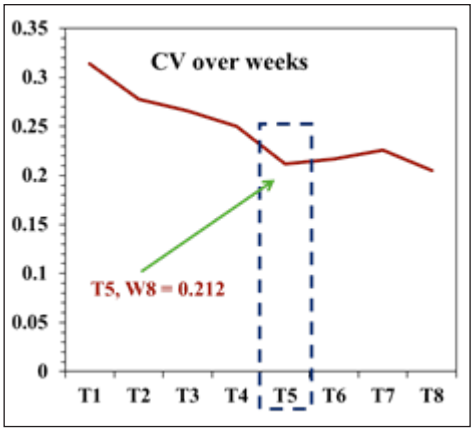
Nitrate (NO_3) Release Behaviour

The nitrate release pattern of the treatment was clearly different over the incubation period (see Figure 2). Generally, fertilised treatments released higher NO_3 than the control. This observation confirms that both mineral and POME-based inputs enhanced N availability in acidic Ultisol. The weekly bars show that during the first to middle of incubation, nitrate release increased progressively across the various treatments, then became more constant in the later weeks. According to this response, nitrate formation was influenced by both the immediately available mineral N fraction and the delayed mineralisation of the organic component.

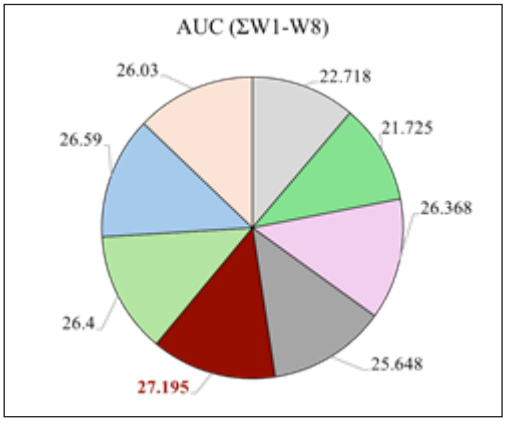
Of all treatments, the organo-mineral and POME-containing formulations exhibited a more prolonged nitrate profile than the unfertilised soil. The treatment response showed variability, suggesting that the organic-to-inorganic ratio influenced the rate and continuity of NO_3 formation. The variability trend presented in Figure 2b reached a lower endpoint at T5 (0.212) at week 8, indicative of more stable nitrate release compared to other treatments at the end of incubation. Such a steadier nitrate supply is often more desirable than a transient release pulse, especially in low-CEC acidic soils, where N loss may occur easily.



(a)



(b)



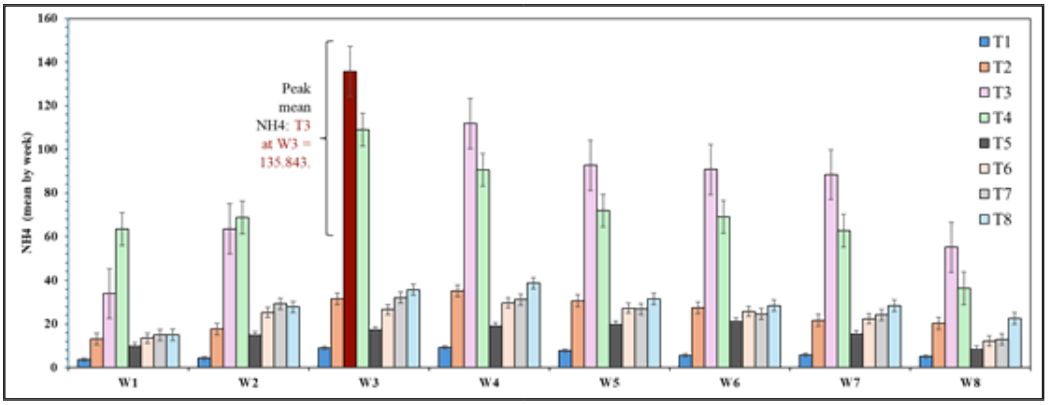
(c)

Figure 2 (a) response trend over weeks of incubation; (b) trend of the parameter measured; (c) relative contribution of treatments in percentage

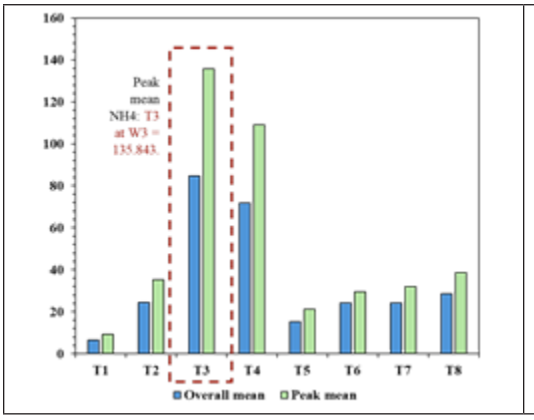
The cumulative distribution in Figure 2c suggests that nitrate release differed among treatments, as certain formulations were more influential than others in total NO_3 release. Considering the findings, it can be said that the blended POME-mineral treatments were more effective than control treatments in sustaining nitrate availability and were also more agronomically balanced than treatments based on a single nutrient (i.e., potassium, magnesium, or sulphate).

Ammonium (NH_4) Release Behaviour

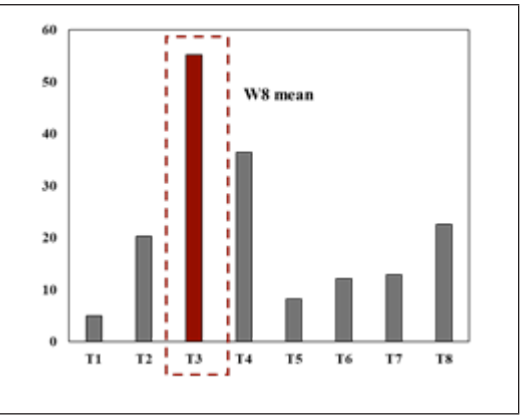
The ammonium response shown in Figure 3 differs noticeably between fast-release and moderate-release treatments. The baseline soil only had a total N content of 0.24%, while the POME sludge had 2.30% N. Hence, when all treatments were fertilised, NH_4 availability increased relative to the control. As can be seen in Figure 3c, the strongest NH_4



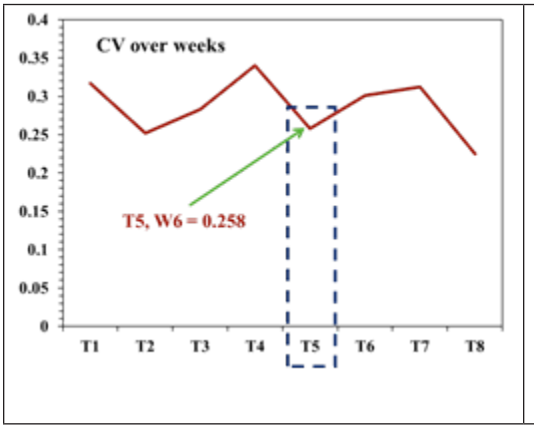
(a)



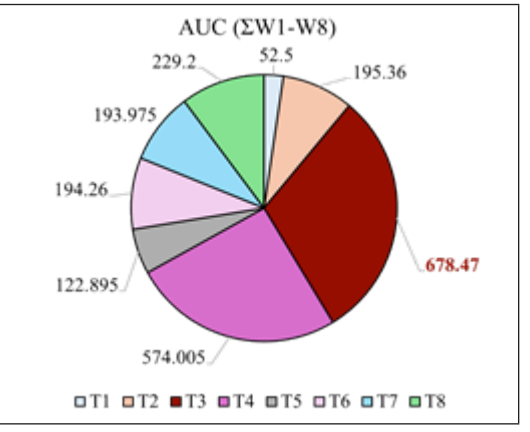
(b)



(c)



(d)



(e)

Figure 3 (a) Ammonium release per treatment per week; (b)Ammonium release comparison of selected treatments; (c) cumulative NH_4 response by treatment; (d) coefficient of variation trend; (e) cumulative NH_4 contribution of treatments

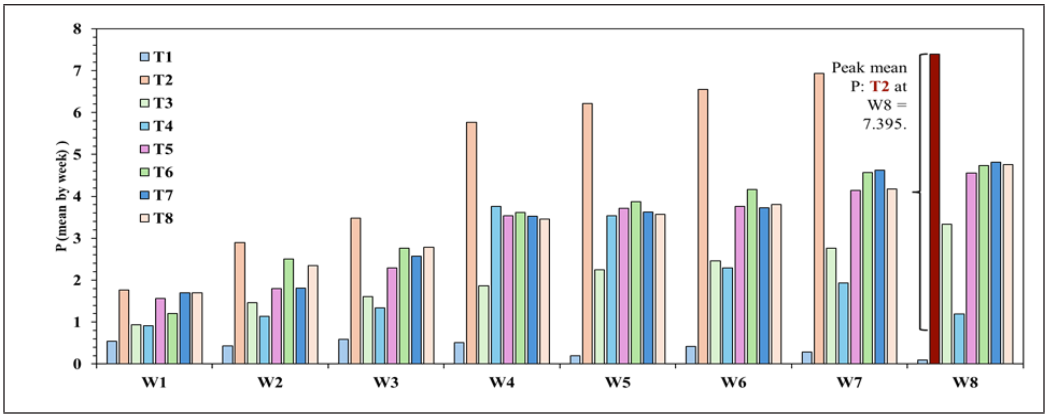
accumulation from all treatments is observed in T3, where POME is dominant, reaching values of 41.0. Hence, in terms of cumulative distribution, it reflects that POME sludge makes a big contribution towards NH_4. Agronomically speaking, the mineral fertiliser treatment probably released NH_4 more rapidly at the early stage, because ammonium sulfate supplies NH_4 in a directly available form. In comparison, the NH_4 from other treatments mineralised more quickly. In other words, the mineral-based treatment provided an immediate supply of NH_4 compared to other treatments. However, treatments that contained POME were better for extended supply. The NH_4 data indicate that the best practical option is not necessarily the treatment with the quickest initial release, but rather the one that maintains NH_4 for longer in low-CEC acidic soil where losses can potentially occur more easily.

Phosphorus Release Behaviour

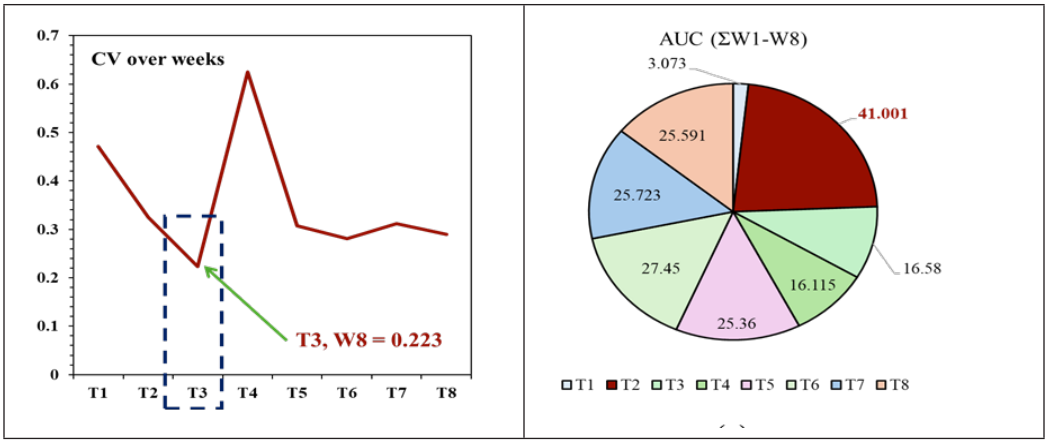
The phosphorus response in Figure 4 was one of the most important findings, as P was the most limiting nutrient in the starting soil. The most obvious evidence is the very sharp early release under the POME-dominant treatment, whereby T3 reached 135.843 at week 3 (Figure 4a). This is consistent with the sludge composition, which had both a strong total P reserve and a high fraction of immediately available P. Essentially, the POME sludge is a genuine P source and not merely an organic carrier. Nonetheless, the conversation ought to go beyond the highest peak value, as the study objective was sustained nutrient availability, not just rapid release. In an acidic Ultisol, this very rapid P release can still be followed by losses due to fixation. So, agronomically, these organo-mineral blends are more meaningful than the peak value alone because immediate P supply is combined with a more relaxed release environment. In the short term, T3 was the best treatment for maximum P release, while the combinations were best suited for sustained usable P over time.

Potassium, Calcium, and Magnesium Release

The release patterns for K, Ca, and Mg, as shown in Figure 5, confirm that the POME sludge contains multiple nutrients and that the base-cation values were very high. According to the cumulative plots, the highest marked value was allocated to the POME treatment dominance, with its cumulative plot values of 479.5 for K in Figure 5c, 895.6 for Ca in Figure 5f and 219.1 for Mg in Figure 5i. These findings are coherent with the sludge chemistry in Table 4, especially its strong Ca content and meaningful K and Mg contents. The relevance of this farming system is extremely high, as the starting Ultisol was extremely low in exchangeable Ca and K and low in Mg.



(a)



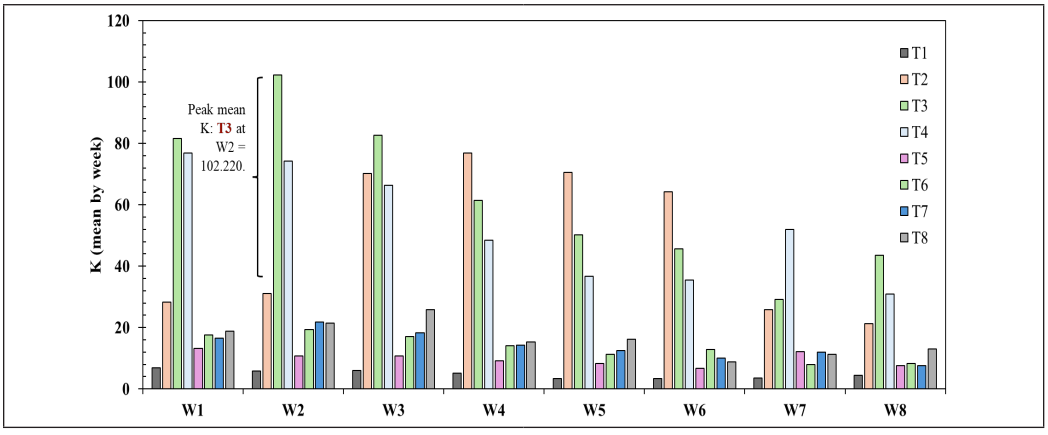
(b) (c)

Figure 4 (a) Weekly phosphorus release across treatments; (b) coefficient of variation trend; (c) phosphorus proportions among treatments

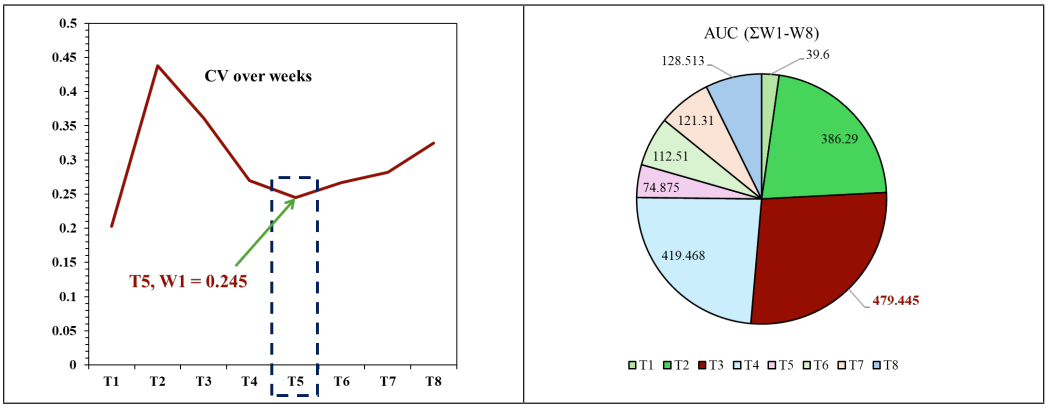
The mineral fertiliser improved these nutrients better, especially dolomite, while the POME-based treatments were more beneficial for total cation contribution. Nonetheless, the most beneficial interpretation is that organo-mineral blends could apply these cations more evenly than a single-source treatment. In soils that are acidic and have low buffering capacity, a balanced pattern is more beneficial than a single sharp pulse, as it helps in reducing the likelihood of nutrient loss and does so over a longer period of time.

Comparison Between Organic, Mineral, And Organo-Mineral Fertilisers

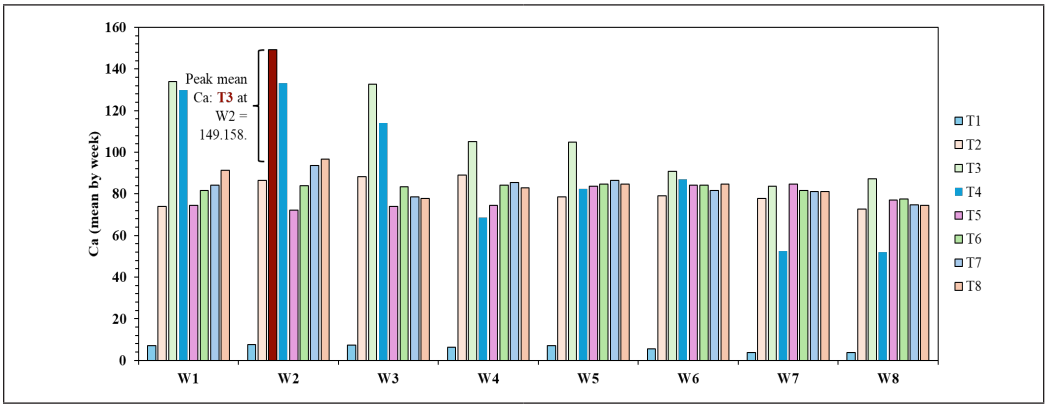
The three fertiliser groups behaved differently; taken together, the results show. The mineral fertiliser was the best option to attain fast release of nutrients that are readily solubilized.



(a)

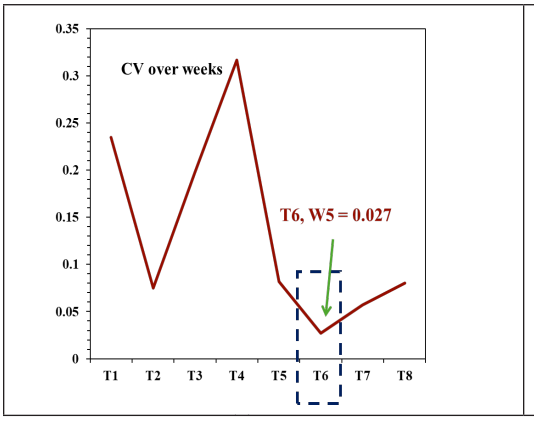


(b) (c)

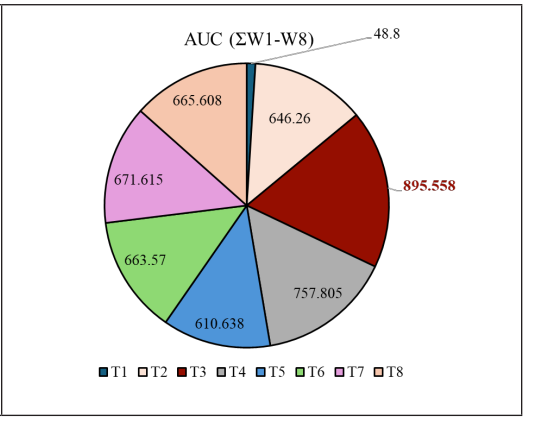


(d)

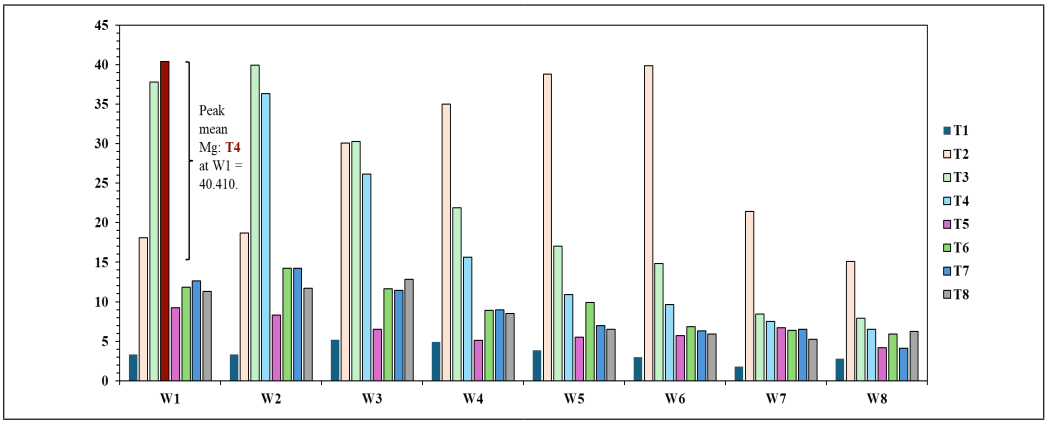
Figure 5. (a) weekly potassium released from treatments; (b) variation coefficient trend for potassium; (c) cumulative contribution of treatments of potassium; (d) weekly calcium released from treatments



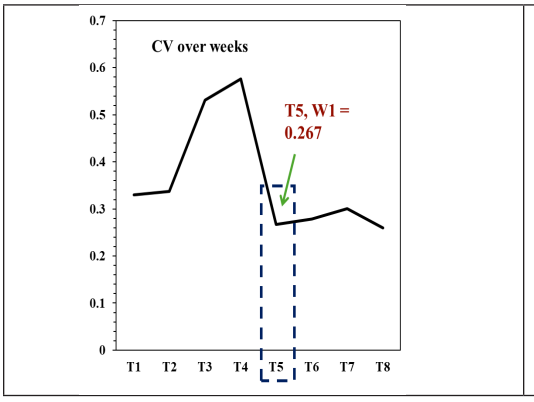
(e)



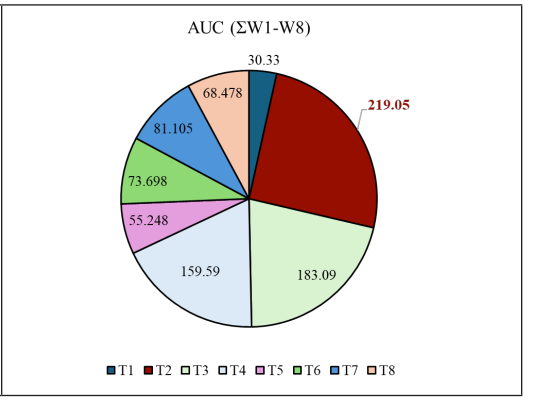
(f)



(g)



(h)



(i)

Figure 5 (*continued*). (e) Variation coefficient trend for calcium; (f) cumulative contribution of treatments for calcium; (g) weekly magnesium released from treatments; (h) variation coefficient trend for magnesium; (i) cumulative contribution of treatments for magnesium

The treatment with the highest nutrient peak and cumulative value for several parameters was POME-only dominant, particularly T3, which makes this treatment the best sample for optimum nutrient supply. Maximum release does not mean best agronomic performance. That means it won't perform well in acidic soils. The organo-mineral mixes were superior for balanced and sustained release, as they involved the immediate beneficial nutrient effect of mineral fertiliser with the buffering and supplementary nutrient effect of POME sludge. According to the results, the most favorable treatment in this study was T5 (80% POME + 20% mineral fertiliser). This means that T3 was best for maximum release, but T5 was best for sustained and practical nutrient management.

Implications For Sustainable Fertiliser Management

The outcomes from this investigation bear practical implications for fertiliser management of acidic tropical soils. The initial soil condition indicated that fertilisers should not only add nutrients to the soil but also improve its buffer capacity, exchangeable base status, and available P for the planted crop. The soil chemical environment must also be enhanced to improve nutrient availability. POME-based formulations can effectively accomplish this; the results indicate. The mineral fertiliser alone can supply nutrients efficiently; however, the POME sludge contributes nutrient reserves, base cations, humic substances and some buffering of acidity. For this reason, the blended formulations performed better as a management strategy. Treatment T5 had the best sustainability performance because it was based on a high proportion of recycled POME material while still providing sufficient mineral input for reliable nutrient release. The practical implication of this research is that the use of organo-mineral blends, especially T5, will be better and more efficient than single-source fertilisers on acidic Ultisols due to a more balanced, sustained and soil-improving nutrient response.

CONCLUSION

In conclusion, this study has demonstrated the nutrient release behaviour of mineral fertiliser, POME-based organic fertiliser, and blended organo-mineral formulations in acidic Ultisols under controlled incubation conditions. The results indicate that the initial soil was severely constrained by strong acidity, very low available P, low CEC and exchangeable base status, while POME sludge offered an important nutrient reserve, particularly for N, P, Ca, Mg and K. Among the tested treatments, it was T3 (120% POME) that produced the strongest nutrient peaks in the short term, particularly for phosphorus and several base cations. This finding indicates that the POME sludge has a high potential for the release of nutrients. Nevertheless, the overall findings suggested that T5, which consisted of 80% POME + 20% mineral fertiliser, gave a more balanced and sustained release pattern, improved soil reaction, and combined the instant benefit of mineral nutrients with the buffering and

nutrient-retention advantage of the organic fraction. Hence, T5 was the best treatment for practical fertiliser management. Due to the possible loss of nutrients from fertilisers and the short durability of fertilisers, T5 is a more appropriate option than either the purely mineral or purely organic treatment in an acidic tropical soil context. Consequently, this research contributes directly to the evidence on POME-derived formulations in acidic Ultisol. In addition, our results indicate that a blended organo-mineral approach is more effective than single-source fertiliser strategies for sustained nutrient availability, less dependency on synthetic fertiliser, and better management of low-fertility tropical soils.

IMPLICATION OF THE STUDY

This study shows that POME-based organo-mineral fertiliser improves acidic Ultisol and supports nutrient availability. T5 gives the best overall performance and provides a more sustainable fertiliser option.

LIMITATION AND RECOMMENDATION FOR FUTURE RESEARCH

This study uses one soil type under laboratory conditions. Future research should test the fertiliser in different soils and field conditions and examine its long-term effects on soil and crop performance.

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Effect of Palm Kernel Cake as a Feeding Substrate on Post-Feeding Development and Reproductive Performance of Black Soldier Fly (*Hermetia illucens*)

Muhammad 'Izzul Islam Ab Mutalib[1], Nurul Syafiqah Noor Idzam[1], Umi Khalsom Mohd Bajuri[1], Razi Ikhwan Md Rashid[1,2], and Ahmad Razali Ishak[1,2]*

[1]Centre for Environmental Health & Safety, Faculty of Health Sciences, Universiti Teknologi Mara (UiTM) Selangor Branch, Puncak Alam Campus, 423000 Puncak Alam, Selangor, Malaysia
[2]Integrated Mosquito Research Group (I-MeRGe), Universiti Teknologi Mara (UiTM) Selangor Branch, Puncak Alam Campus, 423000 Puncak Alam, Selangor, Malaysia

ABSTRACT

The Black Soldier Fly (BSF), *Hermetia illucens*, undergoes a complete life cycle consisting of egg, larval, prepupal, pupal, and adult stages. Feeding occurs only during the larval (BSFL) stage; therefore, the feeding substrate may influence subsequent BSF post-feeding performance. This study evaluated palm kernel cake (PKC), an abundant agro-industrial by-product, as a feeding substrate for BSFL by assessing its effects on adult emergence, egg production, and adult longevity. The feeding substrates comprised 100% PKC and commercial chicken feed (CF) as the control. BSFL were reared on the respective substrates, and their post-feeding development and reproductive performance were compared. Each replicate consisted of 50 randomly selected prepupae, with three replicate cages established for each treatment. Adult emergence, egg production, and adult mortality were monitored and recorded daily and analysed using two-way ANOVA followed by Tukey's multiple-comparison test, with statistical significance set at $p < 0.05$. From the results, feeding substrate influenced post-feeding development and reproductive performance. CF supported faster adult emergence and greater egg production, whereas PKC resulted in delayed emergence and lower egg production but prolonged adult survival. Complete adult emergence was achieved by Day 4 in CF compared with Day 9 in PKC. Cumulative egg production was higher in CF (234.27±12.89 mg) than in PKC (89.60±8.31 mg). Collectively, these findings indicate that although 100% PKC can support successful development and reproduction of BSF, its use

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E-mail addresses:
2022887574@student.uitm.edu.my (Muhammad 'Izzul Islam Ab Mutalib)
2024817062@student.uitm.edu.my (Nurul Syafiqah Noor Idzam)
umibajuri@uitm.edu.my (Umi Khalsom Mohd Bajuri)
raziik9853@uitm.edu.my (Razi Ikhwan Md Rashid)
ahmadr2772@uitm.edu.my (Ahmad Razali Ishak)
* Corresponding author

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is associated with slower post-feeding development and reduced reproductive output, suggesting that substrate optimisation is necessary to improve its suitability for continuous BSF production.

Keywords: Black Soldier Fly, palm kernel cake, post-feeding development

INTRODUCTION

The increasing generation of organic waste and its improper disposal present significant environmental and public health challenges, particularly in countries with limited waste management infrastructure and technology (Kanhai et al., 2021). Conventional disposal methods, such as landfilling and combustion, are widely used due to their low cost but can contribute to pollution and greenhouse gas emissions (Kim et al., 2021). In this context, insect-based bioconversion, specifically using Black Soldier Fly (*Hermetia illucens*) larvae (BSFL), has emerged as a sustainable alternative capable of transforming organic waste into high-value products within a short period (Siddiqui et al., 2022). Moreover, BSFL can feed on and convert a wide range of organic substrates, including agricultural and agro-industrial byproducts, highlighting their potential to reduce waste and environmental impacts (Hancz et al., 2024).

Palm Kernel Cake (PKC), a by-product of palm oil extraction from palm kernels, is abundantly generated in major palm oil-producing countries such as Malaysia and Indonesia (Nugroho et al., 2022; Shukor et al., 2013). As an agro-industrial by-product, PKC contains substantial levels of nutrients, particularly protein and residual fat, indicating its potential as a feeding substrate for BSFL. However, its suitability as a sole feeding substrate may be constrained by its relatively high fibre content, which can limit nutrient availability and larval utilisation (Liew et al., 2022). Previous studies have therefore explored substrate modification approaches, including supplementation (Nugroho et al., 2023), substrate mixing (Bajra et al., 2023), and microbial fermentation (Damanik et al., 2024; Liew et al., 2022), to improve the feeding value of PKC and support BSFL growth (Idzam et al., 2025).

Nevertheless, the suitability of feeding substrate should not be evaluated solely based on larval performance, as nutritional conditions during the feeding stage may also influence subsequent development (Zhang & Puniamoorthy, 2025). These effects are particularly relevant during post-feeding development, when BSFL progresses through the prepupal and pupal stages before adult emergence (Guillaume et al., 2024). During this period, larvae cease feeding, empty their digestive tract, and undergo physiological changes associated with metamorphosis (Rebora et al., 2023). Understanding these post-feeding stages is therefore important, as successful development into reproductively competent adults is essential for maintaining BSF rearing and production systems (Miranda et al., 2019). A recent study further demonstrated that carbohydrate-rich diets with lower protein and fat improved larval growth, female body weight, and egg production, whereas diets high in

both protein and carbohydrates reduced these outcomes, highlighting the carry-over effects of larval diet on adult reproductive performance (Zhang & Puniamoorthy, 2025).

Although previous studies have extensively investigated the effects of feeding substrates on BSFL growth and waste conversion efficiency, comparatively less attention has been given to their subsequent effects on post-feeding development and adult reproductive performance (Guillaume et al., 2024; Rebora et al., 2023). Particularly, information on whether PKC-fed larvae can successfully complete post-feeding development and sustain reproductive performance remains limited. Therefore, this study investigated the effects of PKC as a larval feeding substrate on subsequent adult emergence, egg production, and adult longevity, using commercial chicken feed as the control.

MATERIALS AND METHODS

Substrate Preparation

PKC and commercial CF were purchased locally from MJ FATHONAH Sdn. Bhd. and TVR TERNAKAN RESOURCES, respectively. The proximate composition of CF and PKC was 67.5% and 75.6% total carbohydrate, 19.9% and 15.4% crude protein, 3.8% and 1.9% crude fat, 5.3% and 4.5% ash, and 2.3% and 20.0% crude fibre, respectively. Prior to feeding, both substrates were separately mixed with dechlorinated water to achieve a final water content of 70% (Dzepe et al., 2020).

Prepupae Preparation

Two experimental groups were established in which larvae were fed separately on PKC and CF. The experimental feeding phase began at the neonate stage at 6 days of age and continued until the larvae reached the prepupal stage. Briefly, each container received approximately 485 g of the designated substrate to ensure sufficient substrate for larval growth. Once the larvae entered the prepupal stage, characterised by darkening of the cuticle and migration away from the food source, the actively prepupae were selected from each substrate group for post-feeding development observations (Giannetti et al., 2022).

Experimental Setup and Parameters Assessment

A total of three independent replicates were established for each treatment, with each replicate consisting of 50 randomly selected prepupae transferred into a separate 30 × 30 × 30 cm rearing cage. Adult BSF emergence from each replicate cage was monitored daily following the method described by Ferdousi and Sultana (2021). The number of resulting adults was counted, and the empty pupae shells were separated into small, covered containers to avoid counting the number of adult emergences repeatedly (Figure 1). The experiment was conducted at room temperature (30-32 °C) with an environmental humidity of 69-71% relative humidity (%RH).

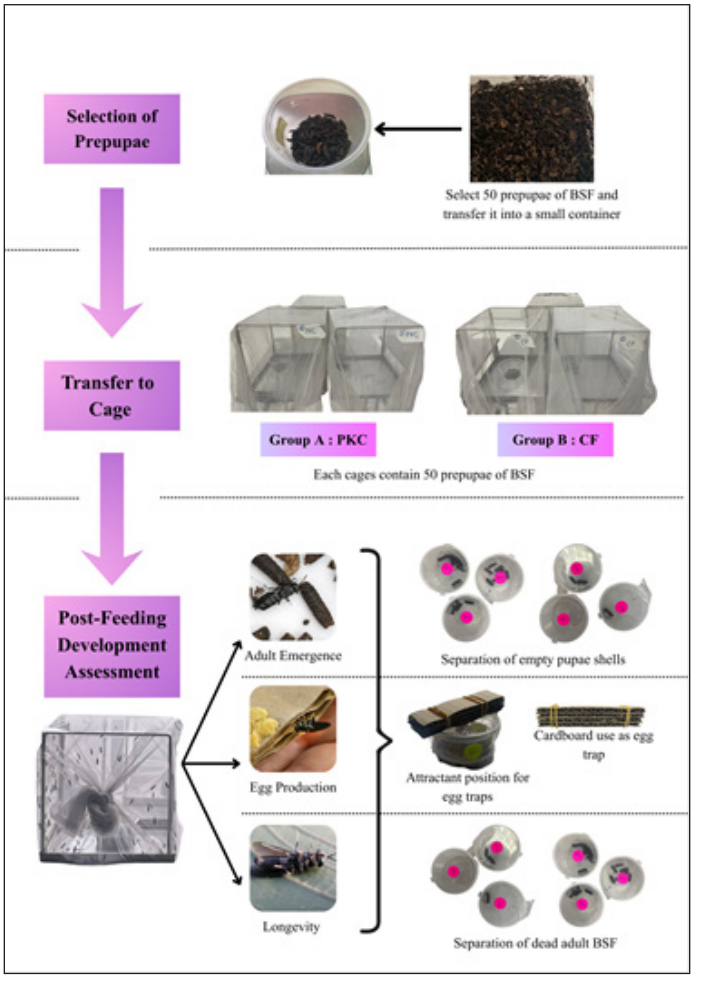


Figure 1. Experimental setup for the studies. Selection of 50 random prepupae from CF and PKC. 3 cages for each treatment represent 3 replications. Parameter evaluation included adult emergence, egg production and longevity

The success rate percentage of adult emergence was calculated using Equation 1:

$$\textit{Success rate of adult emergence, \%:}\ \frac{Number\ of\ Adult\ Flies\ Emerged}{Number\ of\ Initial\ Pupae} \times 100 \quad [1]$$

The egg production of the BSF was evaluated by mating a random 50 adults of BSF (unknown sex) in one cage. The oviposition substrates were placed in a container covered with a net filled with a moist attractant (fermented tofu mix with tempeh) and put underneath the cardboard to trigger the egg-laying response, as shown in Figure 1. The mixture of fermented tofu and tempeh can emit aromatic compounds that attract female flies to lay eggs in cardboard traps (Lestari et al., 2020). The traps were checked every day for 7 days,

and eggs were collected. The egg masses were measured, and the collected data were entered into the data tabulation.

The lifespan of the adult BSF was determined by observing mortality daily until all of them perished. Longevity was given in terms of the mean lifespan of adult BSF for each treatment in days (Resconi et al., 2025). Similar to the adult emergence, the dead flies were separated into a small, closed container to avoid counting the dead flies repeatedly. The percentage of dead flies is calculated using Equation 2:

$$\textit{Percentage of dead adult flies, \%: } \frac{\textit{Number of Dead Adult Flies}}{\textit{Number of Adult Flies Emerge}} \times 100 \qquad [2]$$

Statistical Analysis

All the data that have been collected were analysed through GraphPad Prism (version 10.6.0). Descriptive statistics were used to summarise the success rate of adult flies, egg production and longevity (mean and standard deviation). The comparison of different substates across days was analysed using two-way ANOVA, with $p < 0.05$ defined as significant. In cases where significant results were found, multiple comparisons were carried out to establish the differences between each possible pair, with Tukey's multiple comparison test as the post-hoc analysis being used.

RESULTS AND DISCUSSIONS

Successful Emergence of Adult BSF

Adult emergence differed between the substrate treatments (Figure 2). Based on cumulative emergence (Figure 2a), CF exhibited a faster emergence pattern, reaching 100% emergence by Day 4, whereas PKC showed a slower emergence pattern, requiring up to Day 9. The results supported by the daily emergence data (Figure 2b) showed that emergence in the CF group began on Day 1, peaked on Day 2 (54.67±9.24%), and declined rapidly, with no emergence observed after Day 4. Compared to PKC, it exhibited a more gradual emergence pattern, with emergence continuing until Day 9. Two-way ANOVA revealed a significant treatment × day interaction, $F_{(8, 36)}=6.932$, $p < 0.0001$, and a significant effect of day, $F_{(8, 36)}=10.04$, $p < 0.0001$. However, the overall effect of feeding substrate was not significant, $F_{(1, 36)}=0.001$, $p =0.9744$. Tukey's multiple-comparison test showed significant differences between CF and PKC on Days 1, 2, 4, and 6 ($p < 0.05$).

Egg Production of Adult BSF

Egg production of adult BSF differed between substrate treatments (Figure 3). Based on cumulative egg production (Figure 3a), CF exhibited a higher reproductive output, reaching a total of 234.27±12.89 mg by Day 5 with no further increase thereafter, whereas PKC

showed a gradual increase until Day 10, reaching 89.60±8.31 mg, corresponding to a 61.8% reduction in cumulative egg production relative to the CF control. Referring to daily egg production (Figure 3b), oviposition in the CF group began on Day 1 (64.37±27.24 mg), peaked on Day 2 (126.5±33.36 mg), and declined by Day 3 (18.23±21.20 mg), with no egg production observed after Day 6. In contrast, PKC resulted in lower daily egg production, with oviposition starting on Day 3 (28.13±20.25 mg) and continuing at low levels until

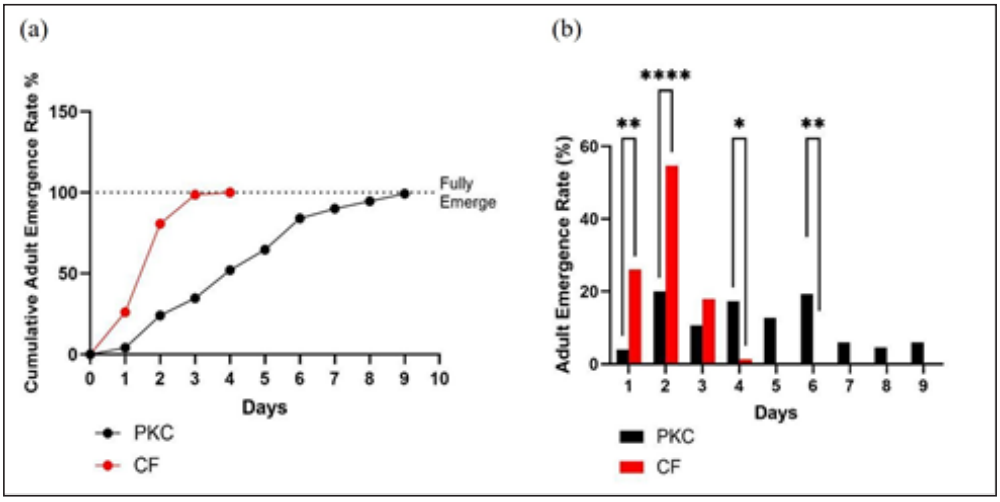


Figure 2. Adult emergence rate of BSF fed PKC and CF as substrate treatment: (a) Cumulative; (b) Daily. Data represent the mean (n = 3)
Note. *Asterisks indicate significant differences

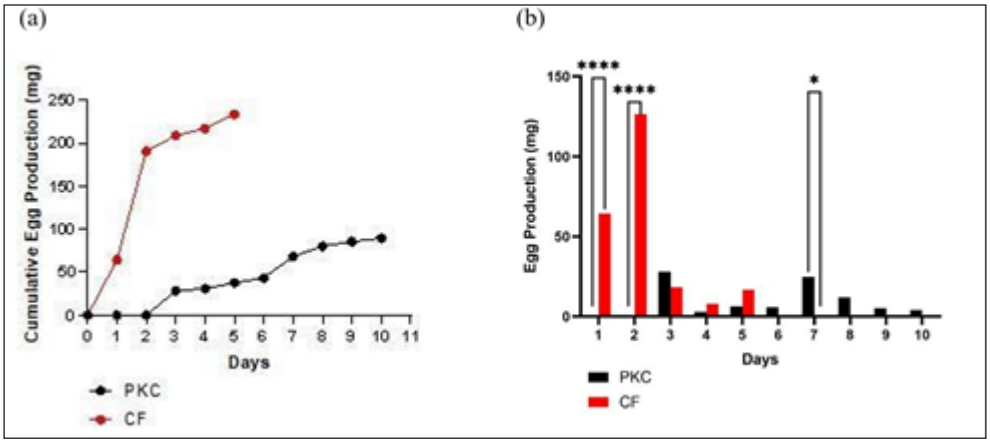


Figure 3. Egg production of BSF fed PKC and CF as substrate treatment: (a) Cumulative Egg Production of Adult BSF across 10 days; (b) Daily Egg Production of Adult BSF across 10 days. Data represent the mean (n = 3)
Note. *Asterisks indicate significant differences

Day 10 (4.00±6.93 mg). Two-way ANOVA revealed significant effects of feeding substrate, $F_{(1, 40)}$=15.20, p = 0.0004, and day, $F_{(9, 40)}$=10.74, p < 0.0001, together with a significant treatment × day interaction, $F_{(9, 40)}$=15.43, p < 0.0001. Tukey's multiple-comparison test showed significant differences between CF and PKC on Days 1, 2, and 7 (p < 0.05).

Longevity of Adult BSF

Adult longevity of BSF differed between substrate treatments (Figure 4). Based on cumulative mortality (Figure 4a), CF exhibited a faster increase in mortality, with most individuals dying earlier, whereas PKC showed a more gradual increase, reaching complete mortality by Day 14. Referring to daily mortality (Figure 4b), low mortality was observed in both CF and PKC groups during the initial days, followed by a marked increase from Day 3 onwards. In the CF group, mortality peaked on Day 5 (>33.33%) and declined thereafter. In contrast, PKC showed lower mortality on Day 5 (20%) but maintained relatively higher mortality on subsequent days, indicating a more extended mortality pattern. Two-way ANOVA revealed a significant effect of day, $F_{(13, 56)}$ =16.32, p < 0.0001, and a significant treatment × day interaction, $F_{(13, 56)}$=3.177, p= 0.0013. However, the overall effect of feeding substrate was not significant, $F_{(1, 56)}$ = 0.002, p = 0.9622. Tukey's multiple-comparison test identified significant differences between CF and PKC on Days 4 and 5 (p < 0.001).

The present study demonstrated that the larval feeding substrate produced distinct subsequent effects on post-feeding performance, with CF supporting earlier adult emergence and higher egg production, while PKC was associated with delayed emergence, reduced reproductive output, and prolonged adult survival. These differences may be associated with

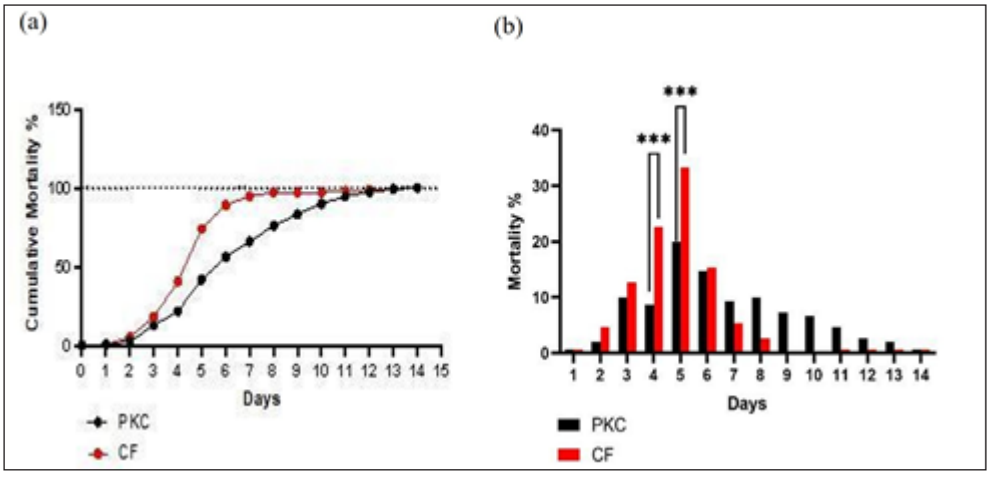


Figure 4. Longevity of BSF fed PKC and CF as substrate treatment: (a) Cumulative Mortality (%) of Adult BSF across 14 days; (b) Daily Mortality (%) of Adult BSF across 14 days. Data represent the mean (n = 3)
Note. *Asterisks indicate significant differences

the contrasting nutritional composition of the larval feeding substrates, as dietary nutrient concentration and macronutrient balance have been shown to influence BSF development time and subsequent adult life-history traits (Binsin et al., 2023; Laursen et al., 2024).

In the present study, CF contained higher crude protein (19.9%) and crude fat (3.8%) and substantially lower crude fibre (2.3%) than PKC, which contained 15.4% crude protein, 1.9% crude fat, and 20.0% crude fibre. The relatively high fibre content of PKC may restrict nutrient accessibility and utilisation by BSFL, as the lignocellulosic components of PKC are difficult for the larvae to digest (Damanik et al., 2024; Liew et al., 2022). Consequently, reduced nutrient availability during larval development may affect nutrient accumulation, as dietary nutrient quality has been shown to influence protein and lipid reserves in the BSF larval fat body, which are important for subsequent metamorphosis and adult reproductive functions (Barragan-Fonseca et al., 2018; Pimentel et al., 2017). This subsequent effect of larval nutrition is supported by Schneider et al. (2025), who demonstrated that dietary protein concentration influenced BSF development beyond the larval stage. The medium and high protein diets shortened development to the prepupal stage and resulted in larger prepupae and adults compared with a low protein diet (Schneider et al., 2025). Such nutritional differences during larval development may therefore contribute to the delayed adult emergence observed in PKC-fed BSFL.

The influence of larval nutrition was also reflected in reproductive performance. Adults emerging from CF-fed larvae produced 234.27 ± 12.89 mg of cumulative egg mass compared with 89.60 ± 8.31 mg from PKC-fed larvae, representing a 61.8% reduction relative to the CF control. This difference may reflect the subsequent effects of nutrient acquisition during larval development, as nutritional reserves accumulated during this stage contribute to adult development and reproductive investment (Laursen et al., 2024; Schneider et al., 2025). The lower egg production observed in the PKC treatment may therefore reflect reduced nutrient accumulation during larval development. Protein availability is particularly relevant to reproductive performance because protein supports vitellogenesis and egg formation in adult insects, while larval diet has been shown to influence adult body size, lifespan, and egg production in BSF (Laursen et al., 2024). Consistent with this, Zhang & Puniamoorthy (2025) demonstrated that larval substrate composition influenced larval growth, adult body weight, oviposition timing, egg production, and hatchability, with larger females generally producing more eggs. Their findings further showed that different compositions of protein, carbohydrate, and fat produced contrasting reproductive outcomes, highlighting the importance of overall dietary nutrient balance rather than individual nutrients alone.

Interestingly, despite the lower reproductive output, adults originating from PKC-fed larvae exhibited a more prolonged survival pattern, reaching complete mortality by Day 14 compared with Day 8 in the CF treatment. This contrasting response indicates that larval feeding substrate may influence adult life-history traits differently, with effects on

reproductive output not necessarily corresponding directly with adult survival. Similarly, Laursen et al. (2024) demonstrated that larval rearing diet influenced both adult lifespan and egg production, supporting the broader subsequent effects of larval nutrition on adult performance. However, prolonged adult survival in the PKC treatment should not necessarily be interpreted as superior reproductive performance, particularly given its substantially lower egg production.

Based on these findings, from a production perspective, the reduced reproductive output observed in the PKC treatment may limit breeder-colony productivity, as lower egg production can reduce the number of larvae available for subsequent production cycles and ultimately constrain biomass production potential. This is supported by Laursen et al. (2024), who highlighted that higher reproductive output can increase biomass production potential and breeding population size, while shorter development time can further improve production turnover in BSF mass-rearing systems. Therefore, although PKC supported successful adult development and reproduction, its delayed emergence and substantially lower egg production may constrain its use as a sole feeding substrate for breeder-colony production. Nevertheless, given its availability and potential for agro-industrial by-product valorisation, appropriate substrate optimisation could improve its suitability for continuous BSF production (Azizi et al., 2021; Idzam et al., 2025).

CONCLUSION

The findings of this study demonstrated that the feeding substrate used during the larval stage influenced the post-feeding development of BSF, including adult emergence, longevity, and egg production. Although BSFL reared on PKC showed delayed adult emergence and lower egg production compared to CF, PKC was still able to support successful adult development and reproduction. This study contributes to the understanding that the suitability of a BSFL feeding substrate should not be evaluated solely based on larval performance, as nutritional conditions during the larval stage may exert subsequent effects on developmental and reproductive traits**.** Given the high generation and abundance of PKC in palm oil-producing regions such as Malaysia, its utilisation in BSFL bioconversion represents a promising alternative that can support sustainable waste management and contribute to the advancement of a circular bioeconomy. Further research should focus on developing appropriate substrate optimisation strategies to enhance the overall suitability of PKC for continuous BSF production.

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Development and Performance Evaluation of a Tractor-Drawn Lemongrass Harvesting Machine

Md Sumon Miah[1,3], Nazmi Mat Nawi[1,2]*, Azmeer Ahmad Shukri[1,2], Md Zakir Hossain[1,4], and Altynbek Usserov[5]

[1]Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

[2]Laboratory of Plantation Systems and Mechanization Technology, Institute of Plantation Studies, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

[3]Farm Machinery and Post-harvest Process Engineering Division, Bangladesh Agricultural Research Institute, Gazipur-1701, Bangladesh

[4]Bangladesh Wheat and Maize Research Institute, Dinajpur-5200, Bangladesh

[5]Research Laboratory Innovative Water Treatment Systems, M. Auezov South Kazakhstan University, Taukehan Street 5, Shymkent 16000, Kazakhstan

ABSTRACT

The rising production of lemongrass has highlighted the need for mechanisation, especially for harvesting operations. Nonetheless, the most common method of harvesting lemongrass remains manual, which is time-consuming and labour-intensive, resulting in increasing costs. The goal of the study was to design and conduct a structural strength analysis of a lemongrass harvesting machine, followed by fabrication, and to evaluate its field performance. Field performance evaluations were conducted at different operational factors, namely forward speed and digger blade entry angle, to provide a comprehensive understanding of the machine's harvesting efficiency, crop damage, field capacity, and limitations. The results indicated increased stress levels with higher entry angles, although they remained below the material's yield strength. The stress, strain, deformation, and factors of safety of the harvester's different parts comply with resistance requirements. Entry angle analysis revealed that a 15º angle combined with a forward speed of 2 km/h provided maximised cutting efficiency while minimising resistance, resulting in optimal performance. However, higher entry angles presented challenges, leading to decreased efficiency and reduced effective field capacity. The harvested yield remains consistently high, ranging from 80% to nearly 90%. The damage percentage was very low, indicating minimal injury during harvesting. The blade of the harvester can penetrate up to the minimum and maximum cutting depths

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E-mail addresses:
sumonfmpe.bari@gmail.com (Md Sumon Miah)
nazmimat@upm.edu.my (Nazmi Mat Nawi)
azmeerahmadshukri@gmail.com (Azmeer Ahmad Shukri)
zakirbwmri@gmail.com (Md Zakir Hossain)
altynbek.usserov@gmail.com (Altynbek Usserov)
* Corresponding author

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required for harvesting lemongrass, but field efficiency is 45% and needs further improvement. The benefit-cost ratio (BCR), payback period, and break-even point of the harvester are 1.20, 1.25 years, and 150 hours annually, respectively. Economic analysis indicates the harvester is viable for small- to medium-scale farmers.

Keywords: Design analysis, field capacity, financial analysis, and lemongrass harvester

INTRODUCTION

Lemongrass is a perennial grass belonging to the *Poaceae* family, cultivated mainly for its aromatic leaves and stalks utilised as a flavouring agent (Gaba et al., 2020). It is a multifunctional plant recognised for its aromatic characteristics and other health advantages. Recent research has emphasised its pharmacological potential, especially in anti-obesity, antidiabetic, and antibacterial effects (Rahhal et al., 2024). Lemongrass demonstrates anti-obesity properties because of its abundant polyphenols, essential oils, and dietary fibre (Brimson et al., 2021). Mechanisms involve the inhibition of digestive enzymes, appetite reduction, and modification of lipid metabolism. The essential oil especially enhances energy expenditure and reduces adipogenesis (Naz et al., 2024; Wisdawati & Razak, 2024). Research involving animal studies indicates significant reductions in fasting blood glucose levels and enhanced glucose tolerance. Limited human trials confirm these findings, indicating that lemongrass may be advantageous in diabetic control (Naz et al., 2024).

Lemongrass extracts showed significant antibacterial properties against pathogens such as Staphylococcus aureus and Candida albicans. The antioxidant properties are remarkable, with ethanol extracts demonstrating considerable effectiveness in neutralising free radicals (Balakrishnan et al., 2014). Furthermore, lemongrass is valued for its sweet citrus flavour, rendering it a favoured component in many culinary uses. The distinctive aroma, mostly attributed to citral, increases the flavour of meals, especially in Asian cuisines. Lemongrass is extensively utilized in soups, curries, and marinades, providing a unique citrus flavor (Khasanah et al., 2024; Prince et al., 2018). Notably, its application as an organic oil product is increasing in popularity due to its medicinal uses for treating different diseases. In Malaysia, lemongrass is utilised as a natural mosquito repellent and is incorporated into the manufacture of perfumes and soaps (Ahmad et al., 2025; Kamaruddin et al., 2022). The global lemongrass oil market is projected to expand from USD 41.98 million to USD 81.43 million by 2028 (Singh, 2000).

In Malaysia, local farmers continue to employ manual harvesting techniques for lemongrass rather than utilising machinery. Consequently, local lemongrass productivity fails to meet demand due to the inefficient harvesting methods employed by local farmers. Manually harvesting lemongrass poses many challenges that may affect efficiency and output. These challenges arise from an intersection of labour-intensive methods, insufficient

technical understanding among manufacturers, and ergonomic considerations that may pose health risks to workers (Kacaribu & Safarudin, 2022). Manual harvesting raises hazards of musculoskeletal disorders resulting from repetitive movements and improper postures. The absence of ergonomic measures in manual harvesting procedures intensifies these health hazards, especially in underdeveloped regions (Jain et al., 2018).

Several researchers designed harvesting machines for root and tuber crops, focusing on crop-specific design concerns and mechanisation levels. Gaadhe et al. (2023) developed a tractor-mounted harvester for carrot harvesting, with an adjusted digging depth of up to 35 cm and refined conveying belt characteristics, resulting in effective lifting with minimal crop damage. In a similar study, Shirwal et al. (2015) assessed a tractor-mounted carrot harvester including a V-shaped digging blade and soil separator, achieving harvesting efficiency of 97.8% with approximately 4.6% damage. Parab et al. (2019) introduced a manually controlled onion harvester utilising a five-bar connection mechanism, indicating possibilities for future automation. Khura et al. (2011) enhanced onion harvesting efficiency by creating a tractor-drawn method designed for specific soil and crop features. The mechanisation of potato harvesting is attracting much focus. Bangar et al. (2016) found essential design parameters, including blade geometry, operational velocity, and soil conditions, that affect tuber damage. Issa et al. (2020) developed and assessed a tractor-mounted potato digger, highlighting the impact of vibration frequency on lifting efficiency and tuber quality. Blok et al. (2025) recently presented a harvester-mounted system using a 3D form completion network, facilitating real-time potato yield calculation via RGB-D photography, thereby merging AI with harvesting. Nagendra et al. (2018) designed a tractor-drawn harvester for ginger that optimised elevator angle and speed ratios to enhance crop recovery, whereas Sanjay et al. (2015) engineered an engine-powered ginger harvester that emphasised blade design and chain drive parameters, thereby reducing labour intensity and minimising crop loss.

In contrast to root and tuber crops like carrots, onions, potatoes, and ginger, which are collected by removing singular underground storage organs, lemongrass develops in dense fibrous clusters with a broad root network and several closely arranged tillers. Effective harvesting of lemongrass necessitates severing the root mass at a suitable depth while preserving the clump's structure and reducing harm to the stems and roots. Consequently, harvesting systems intended for root and tuber crops are inappropriate for lemongrass because of the variations in crop morphology, root architecture, and harvesting necessities. Therefore, this research project aims to design and develop a tractor-mounted lemongrass harvester featuring a seven-blade digging system, vibrating conveyor separator and rubber-roller transport mechanism. These design features were developed to improve harvesting efficiency, reduce losses, and crop damage.

The local lemongrass growing sector can greatly benefit from the design of an economical harvester that employs the same energy source as a tractor. The structural efficiency of the designed lemongrass harvester was computationally modelled using SolidWorks for three-dimensional CAD modelling and finite element analysis (FEA) before fabrication. This method allowed for efficient design validation and cut down on

the need for redundant physical prototypes and design changes. The right material has also been chosen to guarantee the stiffness, strength, and stability of the body structure (Jamari et al., 2022). Additionally, the FEA conducted using SolidWorks simulation was used to evaluate the structural performance of the lemongrass harvester. The research was then conducted using an experimental testing design once computer simulation findings were obtained. Thus, the goal of this project was to design and develop a tractor-operated harvester for the harvesting of lemongrass. The performance of the developed harvester was assessed in the experimental field.

MATERIALS AND METHODS

The conception and preliminary design evaluations of the lemongrass harvester were performed to ascertain the viability of the machine structure. The harvester's design comprises essential components like the digger blade, three-point hitch, and body frame. Analyses of stress, strain, displacement, and factor of safety were conducted through design evaluation under various applied forces (Figure 1). Based on these assessments, essential design changes were implemented to guarantee structural stability. Upon confirmation, the fabrication of the lemongrass harvester was executed utilising suitable materials available in the local market. During evaluation, specific test factors such as depth of cut and harvesting efficiency were taken into account. Performance analysis assessed how much of crop loss or unharvested yield. Ultimately, the comprehensive performance assessment served as the foundation for endorsing the harvester for field deployment.

Design Considerations

The lemongrass harvesting machine was precisely designed, considering several criteria, to guarantee optimum efficiency. These elements included the grass uprooting system, the ease of fabrication and adjustment, and the mechanism for placing lemongrass after harvest. Moreover, the proposed harvester could harvest 73 cm of lemongrass in a single pass. Furthermore, the harvester was constructed to meet some design requirements including (i) capability to harvest different sizes of lemongrass, (ii) flexibility to accommodate different harvesting depths, and (iii) adjustable rpm of the conveyor for minimum damage to harvested lemongrass. These design requirements were evaluated through computational design analysis and considered in relation to the cultural practices for lemongrass harvesting in Malaysia.

Computational Design and Analysis

Design of Lemongrass Harvester

The design process flowchart clearly illustrates the procedure for designing the machine (Figure 1). The computational design was performed using the SolidWorks 2023 software. The harvester design underwent a design analysis to improve field capacity and usability.

Three-dimensional computer-aided design (3D-CAD) modelling of the lemongrass harvester is shown in Figure 2. Computer-aided engineering (CAE) and SolidWorks simulation tools were used to perform a static force and strength analysis (Miah et al., 2023).

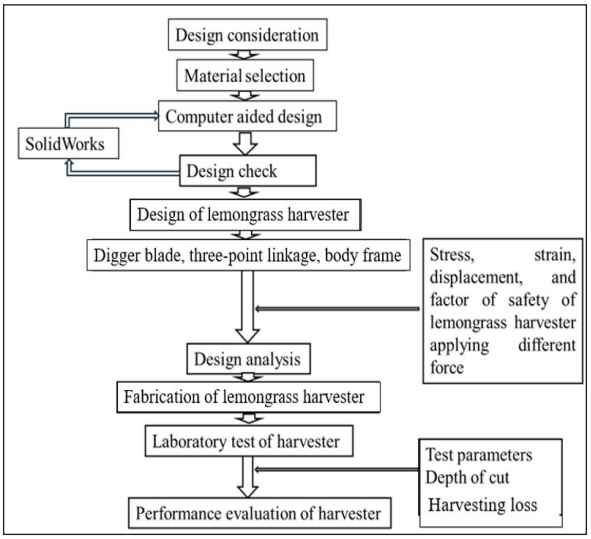


Figure 1. Design process and performance evaluation flowchart of lemongrass harvester

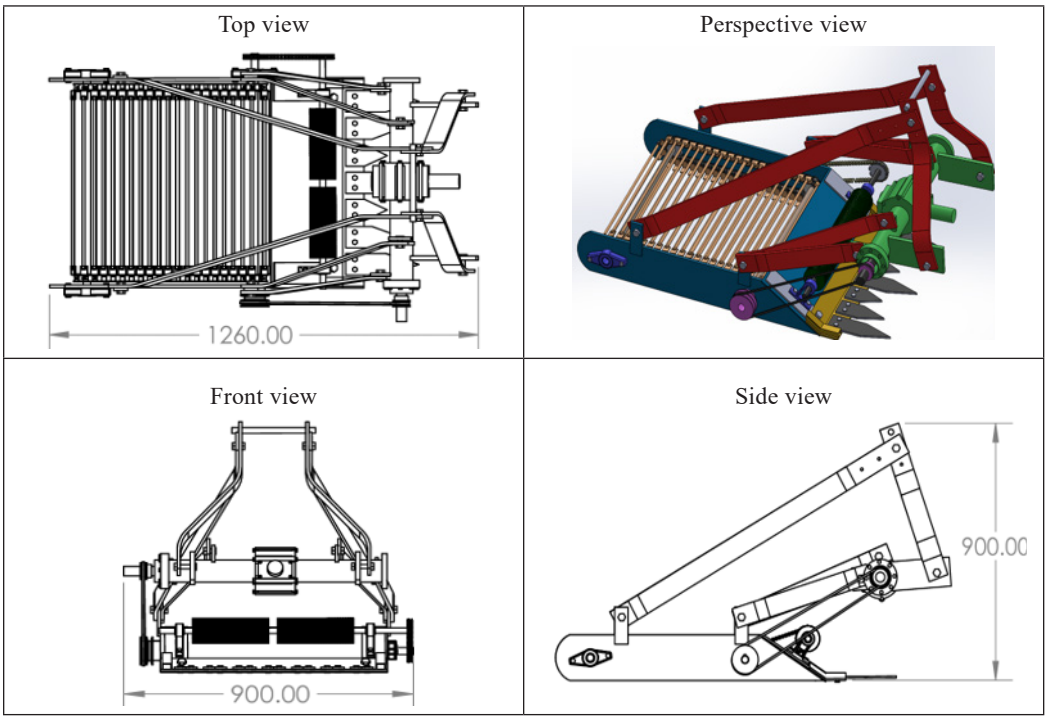


Figure 2. Different views of the lemongrass harvester

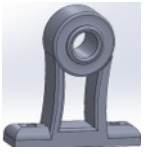
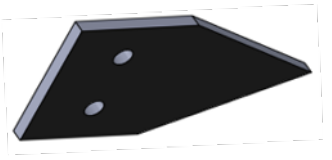
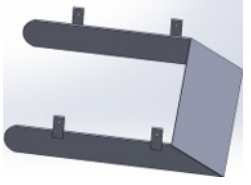
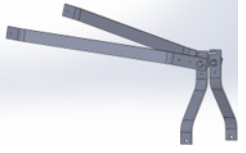
Structural Design and Description of Different Parts of Lemongrass Harvester

A tractor-operated lemongrass harvester was designed and developed at the Farm Machinery Laboratory, Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia. The main principal parts of the harvester are a digger blade, chain and sprocket, belt and pulley, conveyor belt system, support frame and rubber roller (Table 1). The blade is the main part of the digging system for uprooting lemongrass from the soil. The purpose is to harvest the lemongrass from the field while minimising soil displacement and preventing damage. The main frame serves as the foundational basis for the device, ensuring the operational components are compact. It holds all the parts of the harvester and makes an interconnection among them for easy passing of harvested lemongrass. It also protects the conveyor from foreign objects that enter during the harvesting process. The support frame is another important part that makes the connection between the harvester and the tractor. It is linked using a 3-point linkage, where the tractor can easily raise and lower the harvester and also apply draft force to move forward. The primary purpose of the rubber roller is to pull the harvested lemongrass forward to the conveyor for separating the soil from the root.

The blade is a component of the digging system used for harvesting lemongrass. This blade penetrates into the soil until it reaches the root zone of the lemongrass. The blade must penetrate the soil to a depth of 2.0 cm to 7.0 cm to reach the root zone. This blade is suitable for use on flat terrain; nevertheless, its application on uneven surfaces may result in failure. In order to provide sufficient support for the entire cutting assembly and to ensure progressive soil penetration across the working width, the digging system was built with seven blades of three different sizes. When multiple blade sizes are used instead of engaging the entire working width at once, the soil-engagement load is distributed more evenly, and the digging system encounters less initial soil resistance.

Additionally, this design minimises disturbance to the surrounding soil while facilitating the lifting of the clumps of lemongrass roots and improving soil flow around the blades. In order to promote smooth soil flow and minimise the possibility of blockage by soil clods, weeds, and crop residue, the digging system was built with a V-shaped blade arrangement (Figure 3) and suitable spacing between the seven blades. The blade spacing allows sufficient space for weeds and plant residues to move through the digging system, while the V-shaped design guides the soil laterally from the centre of the blade unit. The V-shaped digger blade is a crucial element of root digger harvesting equipment, facilitating the efficient and precise extraction of root crops from the soil during harvesting. A support frame with three predetermined nut-and-bolt mounting positions was used to modify the digger blade entry angle. A fixed blade entrance angle of 15°, 20°, or 30° with respect to the horizontal ground surface was associated with each mounting position. Before each field experiment, the support frame was secured at the proper mounting position to achieve the desired angle.

Table 1
Specification of different parts of the harvester

Name of Different Parts	Schematic Drawing	Dimension, mm	Role of the Parts
Chain and sprocket		Length- 744	Transfers the power from the conveyor belt to the rubber roller shaft
UCP bearing		UCP 204	Support the rubber roller Hold the rubber roller shaft
Digger blade		(L×W): 145x75 (S) 191x75 (M) 255×75 (L)	Digging the soil to uproot the lemongrass
Rubber roller		Diameter-90 Length-245	Pull the harvested lemongrass to the conveyor
Sprocket		Diameter 82 Teeth no. 9	Rotating the conveyor belt
Main frame		Size: 1023×730 Thickness: 10	To support and protect the conveyor from foreign objects.
Support frame		Thickness: 20	Connecting between tractor and harvester.

The vibrating conveyor is an important part of the lemongrass harvester (Figure 4). During harvesting, this conveyor has many functions. The first function is to continuously carry the lemongrass from the blade to the delivery end. The secondary function of this conveyor is to clean the roots of harvested lemongrass. It will detach the dirt from the roots

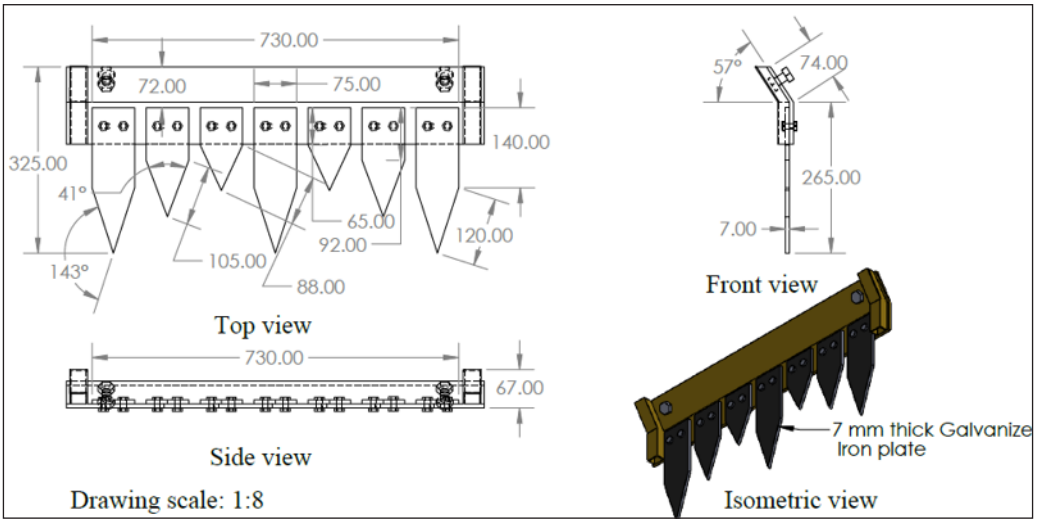


Figure 3. Different views of the digging system

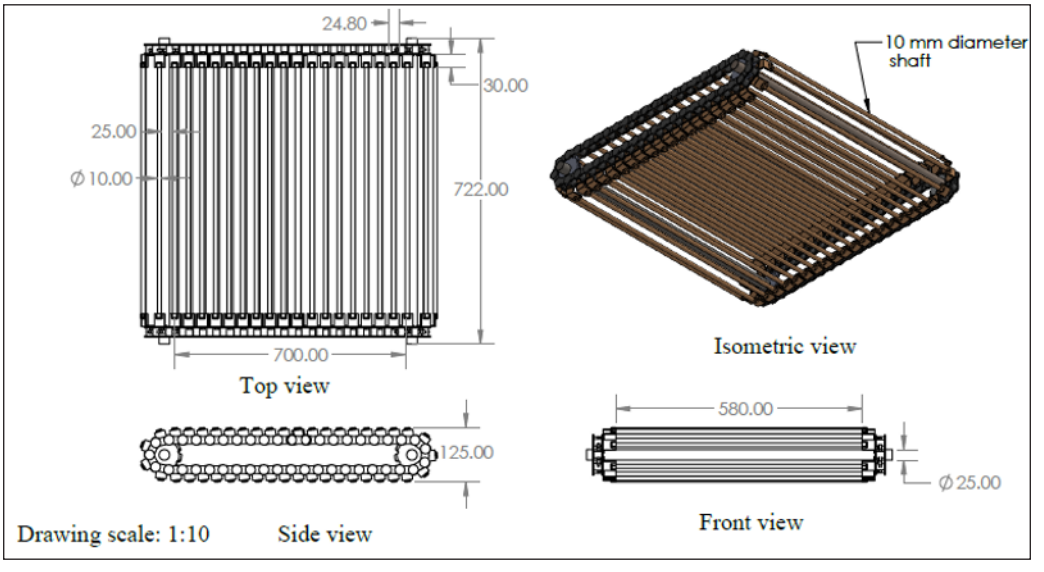


Figure 4. Different views of the conveyor on the harvester

of lemongrass; it is also known as a separator. The lemongrass becomes detached from the soil using vibration. This conveyor is designed to vibrate throughout the separating process. The chain must be adequately free, yet not excessively so, to prevent conveyor vibration that could displace the chain. The parallel rods used to make up the vibrating conveyor separator were clearly spaced apart by 25 mm. This spacing was chosen to minimise harvesting losses during conveyor operation by allowing dirt and small soil clods to pass through the separator while keeping the harvested lemongrass clumps.

Excavation Force

Loading on blades caused stress and deformation, negatively impacting the structural material. The Odey soil force model was used to calculate loads and predict total excavation forces (Odey, 2015). Figure 5 illustrates a wedge-shaped blade zone with a width w positioned in front of the tool, accompanied by an indeterminate soil failure angle. Each side features circular segments with a radius (R) that extend to the point directly opposite the bottom blade tip (S) on both sides. R and S depend upon the angle of the wedge (β). The volume of soil displaced determines the critical wedge angle, and factors such as the blade's slenderness and the necessity to convey material to the blade's slides may influence its critical wedge angle value. The angle is contingent upon two factors: blade entry angle and soil strength.

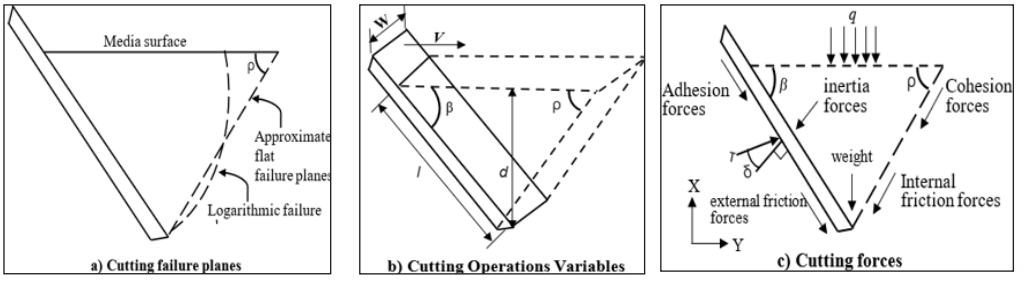


Figure 5. Odey model - three-dimensional soil cutting model (Odey, 2015)

Drag force, angle of wedge and inertia were determined for the blade according to Equations 1, 2, and 3, respectively (Odey, 2015).

$$Total\ Force(P) = \left(\Upsilon g d^2 N_\Upsilon + cdNN_c + C_a dN_{ca} + qdN_q + \Upsilon v^2 dN_a\right)W \quad [1]$$

$$[Angle\ of\ wedge\ (\beta) = \arctan\left(\frac{1}{10.255(130-2\Theta)^{(-0.4316)}}\right) - \left(\frac{1}{\tan(130-2\Theta)(\frac{180}{3.4150})}\right) \quad [2]$$

$$Inertia\ (N_a) = \frac{tan\beta + \cot(\beta + \Theta)}{[\cos(\alpha + \delta) + sin(\alpha + \delta)\cot(\beta + \Theta)][1 + tan\beta\cot\alpha} \quad [3]$$

Equation 1 define P as the total force in kN, γ as the soil specific weight in kN/m^3, d as the tool working depth in m, Nγ as the dimensionless gravity coefficient, c as the soil cohesion in kPa, Nc as the dimensionless cohesion coefficient, ca as the soil-tool adhesion

in kPa, Nca as the dimensionless adhesion coefficient, q as the surface surcharge pressure in kPa, Nq as the dimensionless surcharge pressure coefficient, v as the tool speed in m/s, Na as the dimensionless inertial coefficient, and w as the tool width in m. The inertia coefficient γ, along with Nc, Nq, and Nca, are variables influenced by both the frictional strength of the soil and the geometric characteristics of the blade, as well as the strength qualities between the blade and the soil. The values of the gravity coefficient (Nγ), cohesion coefficient (Nc), and surcharge pressure coefficient (Nq) were 1.05, 1.38, and 0, respectively. These parameters are essential for the determination of draft forces in sandy soil. The values of different factors (θ (30º), γ (15 kN/m^3), c (10 kN/m^2), δ (22º), Ca (0 kN/m^2), and q (0 kPa)) are determined according to the slope of the harvester's blade and soil properties. These equations estimate the draft force exerted on the digger blade by considering the soil characteristics, blade design, and operational parameters.

Design Analysis of Lemongrass Harvester

In order to handle different loads placed on the machine, the simulation procedure must guarantee the proper safety factor, stress, and strain of the materials. In order to measure the failure of the materials in a uniaxial tensile test, the Huber-Mises-Hencky theory was used in this research (Ammarullah et al., 2023). The materials in the current computer simulation model are assumed to be consistent, isotropic, and linearly elastic (Ammarullah et al., 2021). Huber-Mises-Hencky's theory was used to compute and lower the stress, strain, displacement, and factor of safety for the harvester's most important components, including the big blade, digger blade assembly, and three-point hitch, using SolidWorks simulation (Dudda, 2018; Miah et al., 2022, 2023).

Additionally, in the design analysis, the geometric model and other relevant design parameters are taken into account to address the stress, strain, displacement, and factor of safety of various elements, as these factors are utilised in many mechanical components and would affect the overall performance of the machine (Jamari et al., 2021; Tauviqirrahman et al., 2023). Except for a portion of the chain, sprocket, and bearing, which are constructed of mild steel, most of the harvester is made of ASTM A36 steel, and mechanical properties are given in Table 2. ASTM A36 was selected due to its optimal combination of mechanical strength, weldability, accessibility, and cost-effectiveness, rendering it one of the most popular structural steels for agricultural machinery. Nevertheless, Figures 2a, 3 and 4, as well as Table 3, display the dimensions and specifications of the machine's various parts together with their typical viewpoints. However, stress analysis was carried out utilising SolidWorks software in order to enhance usability and expand the field capacity of the suggested harvester. For safety concerns, the big blade, digger blade assembly, and three-point hitch were the primary components examined. The Huber-Mises-Hencky theory was applied in this analysis to reduce displacement and stress (Dudda, 2018).

Table 2
Mechanical properties of ASTM A36 steel

Property	Value	Units
Elastic Modulus	2e+11	N/m^2
Poisson's Ratio	0.26	-
Shear Modulus	7.93e+10	N/m^2
Mass Density	7850	Kg/m^3
Tensile Strength	400000000	N/m^2
Yield Strength	250000000	N/m^2

Table 3
Technical specifications of the lemongrass harvesting machine

Characteristic	Description
Machine Dimension, cm (length × height × width)	126.00 × 90.00 × 90.00
Connection Method	3-point linkage
Working Width, cm	73.0
Excavation Depth, cm	5.0
Weight, kg	200

Fabrication of the Lemongrass Harvester

After the CAD design and computer-aided engineering (CAE) processes, the proposed design was fabricated utilising locally sourced materials (Figure 6). The overall dimensions are 1260 mm × 900 mm x 900 mm (Table 3). The fabrication expense for the harvester was USD 1500.

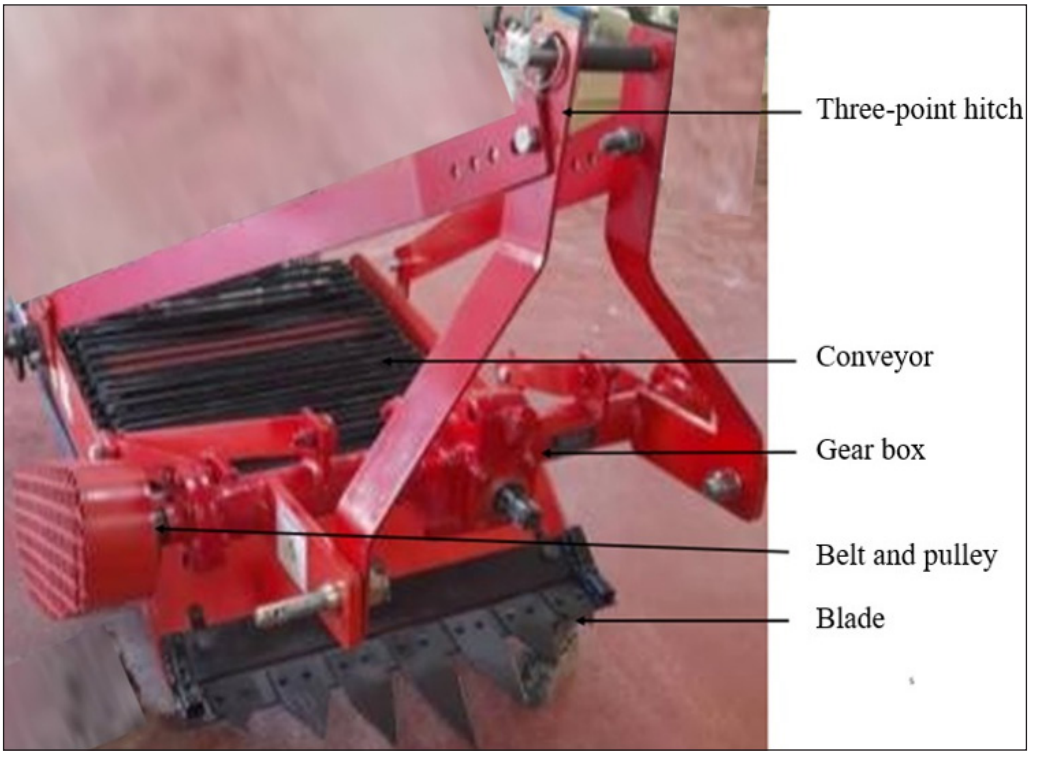


Figure 6. Structure of lemongrass harvesting machine

Working Principle of the Lemongrass Harvester

The harvester has to be connected to a tractor in order to operate correctly. Because the harvester's belt and pulley were connected to a PTO (power take-off) shaft, the conveyor and rubber roller must likewise revolve in the same direction as the PTO shaft. Power was transferred from the tractor PTO shaft to the conveyor shaft through a pulley and belt. Another side of the conveyor shaft was connected to the rubber roller shaft through a chain and sprocket. When the tractor moves forward, the digger blade enters the soil due to its inclination. The blade would uproot the lemongrass and pass it to the rubber roller; some soil would drop due to the action of the rubber roller. Then, the harvested lemongrass would come onto the conveyor vibration belt, and the soil from the root was removed due to the vibration and biting of the conveyor rod. To minimise the crop rollback toward the blade assembly and enable a smooth passage of the harvested lemongrass from the digging unit to the vibrating conveyor, these comparatively low inclination angles were chosen. Additionally, the pulley transmission system altered the conveyor's rotational speed by 1.8 times, enabling the harvested crop to be smoothly transported and minimising the risk of crop rollback and clogging.

Experiment Site and Field Test

The field experiment was conducted at Unit Sayuran, Universiti Putra Malaysia (UPM), and the plot size was 20 × 20 m. The harvester was set to run about 14.7 m in length; each entry angle was repeated three times. The experimental arrangement consisted of a Kubota M6040 tractor, with a rated power of 62 hp and a PTO rotational speed of 540 rpm (Figure 7). The conveyor speed was kept at 135 rpm, the rubber roller speed at



Figure 7. Lemongrass harvester operates in the field

220 rpm and the transmission ratio was fixed at 1:4. The experiment was arranged with three digger entry angles (15º, 20º, and 30º), and these data were analysed using SPSS Statistics 25. The criteria evaluated in the field test included the quantity of unharvested lemongrass, the cutting depth, and the field capacity. This experiment utilised sandy loam soil with a bulk density of 1420 kg/m³ and moisture content of 22.12%. To measure the corresponding performance characteristics, the equipment comprised a digital weighing balance, measuring tape, stopwatch, tachometer, moisture meter, and digital angle finder, which were used in this study. The age of lemongrass at harvest was 205 days, and the chump population was 18060 per hectare. The planting and line-to-line spacing were 60 × 60 cm, and the average root depth was 7.56 cm.

Harvesting Loss and Crop Damage

Each time that harvest was carried out, the harvested area was inspected to assess the damage to the lemongrass and to measure the harvesting loss. The total number of lemongrass clumps in the experimental area was counted. Clumps with clear mechanical damage from the harvesting operation were considered damaged (Equation 5), while clumps left in the field after harvest were considered unharvested. In the experiment, harvesting loss was defined as the percentage of lemongrass remaining in the field after harvesting, as shown in Equation 4:

$$Harvesting\ loss\ (\%) = \frac{NMHL}{TNL} \times 100 \quad [4]$$

Where NMHL is the number of unharvested lemongrass, and TNL is the total number of lemongrass in the unit area.

$$\text{Damage } (\%) = \frac{MD}{TNL} \times 100 \quad [5]$$

Where MD is the number of mechanically damaged lemongrass

Cutting Depth

It is a very important parameter of a lemongrass harvesting machine because the harvester needs to cut the soil and uproot the lemongrass. Machine performance depends on the cutting depth of the harvester; otherwise, the chance of damage will increase. So, the machine should be set at the proper depth for accurate harvesting. It is very important to know the maximum and minimum depth of cutting of the harvester. The maximum and minimum cutting depths were measured in the field after each lemongrass harvester ran. The cutting depth was measured using a measuring tape from the original soil surface to the bottom of the cut after the places corresponding to the deepest and shallowest cuts were

initially determined by eye inspection. Thirty measurements of the highest cutting depth and thirty measurements of the minimum cutting depth were taken for every treatment. The data from the three repetitions of the best treatment were utilised for statistical analysis and the creation of Kernel Density Estimation (KDE) curves.

Forward Speed

A timer and a measuring tape were utilised to quantify the time taken to travel a predetermined distance. The time required to go this distance was measured with a stopwatch. The method was conducted three times, and the average forward speed was computed according to Equation 6.

$$S = \frac{d}{t} \quad [6]$$

Where S is speed (km/h), d is driven length (km), and t is driven time period (h).

Field Capacity

Field capacity refers to the rate at which an agricultural machine performs tasks in a field within a specified timeframe. It is commonly expressed in hectares per hour (ha/h). Field capacity (FC) comprises theoretical field capacity (TFC) and effective field capacity (EFC). The TFC represents the actual rate of field coverage attained during a certain duration of harvester operation. During the operation of the harvester, EFC can be defined as the actual field rate achieved during a specified duration. The study seeks to enhance harvesting efficiency relative to conventional harvesting. The TFC and EFC were computed according to Equations 7 and 8, respectively (Hoque & Miah, 2015).

$$\text{TFC (hah}^{-1}) = \frac{SW}{10} \quad [7]$$

Where W is the width of coverage (m), and S is the forward speed (km/h)

$$\text{EFC (hah}^{-1}) = \frac{Actual\ \ field\ \ coverage\ \ (ha)}{Actual\ \ time\ \ of\ \ operation\ \ (h)} \quad [8]$$

Generally, the field efficiency of the harvester was calculated using TFC and EFC as shown in Equation 9.

$$\text{Field efficiency (\%)} = \frac{EFC}{TFC} \times 100 \quad [9]$$

Cost Calculation

The financial analysis of the developed lemongrass harvester was conducted in accordance with the established protocols for agricultural machinery management outlined by Hunt (2008). The formulas and assumptions employed to calculate the fixed costs, variable costs, yearly gross income, benefit-cost ratio (BCR), and payback period are outlined below. The cost calculation was based on the fixed and variable costs of the lemongrass harvester. The associated cost parameters were as follows.

i. Purchase cost of the harvester
ii. Salvage value of the harvester
iii. Machine life, years
iv. Bank interest rate, %
v. Annual usage of harvester, h
vi. Operator fee, USD/ha
vii. Fuel consumption, L/h
viii. Repair and maintenance expenses; and tractor rental cost (considering Malaysian conditions). The total operating cost of the developed lemongrass harvester depends on its fixed and variable costs. Fixed costs remain constant regardless of machine use, whereas variable costs occur only when the harvester is operated, as shown in Equation 10 (Hunt, 2008).

$$AC = FC + VC \quad [10]$$

The detailed cost calculation for the developed harvester is given in Table 7. Net benefit was also calculated by deducting cost from total benefit.

Fixed Cost

Fixed costs are constant and exist regardless of the utilisation of the harvester. The cost of the harvester was assessed on a yearly basis. The fixed cost of the harvester was determined using the capital consumption (CC) approach as shown in Equation 11. A capital recovery factor (CRF) consolidates total depreciation and interest fluctuations into a series of uniform annual payments at compound interest, as shown in Equation 12. This payment, along with the interest on the undervalued amount, is utilised to assess the capital consumption of agricultural machinery (Hunt, 2008).

$$\text{CC} = (P - S)CRF + S \times i \quad [11]$$

$$\text{CRF}=\frac{i(1+i)^{L}}{(1+i)^{L}-1} \quad [12]$$

Where P is the purchase price of the harvester (USD, L is the life of the harvester (yr, i is the bank interest rate (%, and S is the salvage value of the harvester (10% of P).

Variable Costs (VC)

Variable costs are associated with the operation of the lemongrass harvester, and they occur only when the harvester is used. Variable costs of the harvester are usually expressed on an hourly basis.

Break-Even point (BEP)

In the context of agricultural equipment, the break-even point (BEP) represents the least yearly utilisation of the machinery (hours/year) necessary to recoup all ownership and operational expenses, as shown in Equation 13.

$$\text{BEP}=\frac{FC}{(R-VC)}\times 100 \quad [13]$$

Where FC is an annual fixed cost (USD/year), R is a custom hiring charge or service rate (USD/h), and VC is a variable operating cost (USD/h).

RESULT AND DISCUSSION

Excavation Force Relation with Entry Angle

Odey model predicts that the excavation force of a tractor-operated lemongrass harvesting machine will increase with an increase in the entry angle (Table 4). At a penetration depth of 0.12 m and a tractor speed of 0.27 m/s, the excavation force incrementally increased from 3.056 kN at an entrance angle of 15° to 3.188 kN at 20°, ultimately attaining 3.398 kN at 30°. This pattern indicates that elevated entrance angles necessitate greater power, probably because of increased soil resistance and an expanded contact area during penetration. The

Table 4
Excavation force values of different entry angles

Depth Penetration (m)	Tractor Speed (m/s)	Entry angle (°)	Excavation force (kN)
0.12	0.27	15	3.056
		20	3.188
		30	3.398

identified correlation emphasises the impact of geometric features on excavation mechanics, essential for enhancing machine design and performance. This soil resistance force will help in the design analysis of different parts of the lemongrass harvester.

Design Analysis Results.

The design analysis outcomes for the big blade, digger blade assembly, and three-point hitch of the lemongrass harvester are presented in Figure 8, Figure 9, and Figure 10, respectively. The colours red, green, and blue in the figures represent the highest, medium, and lowest magnitudes, respectively. The design analyses were conducted based on the loads applied to certain components of the harvester. Accordingly, forces of 160 N, 400 N, and 4000 N were considered for the big blade, digger blade assembly, and three-point hitch, respectively, as these represent the maximum forces applied to the relevant components.

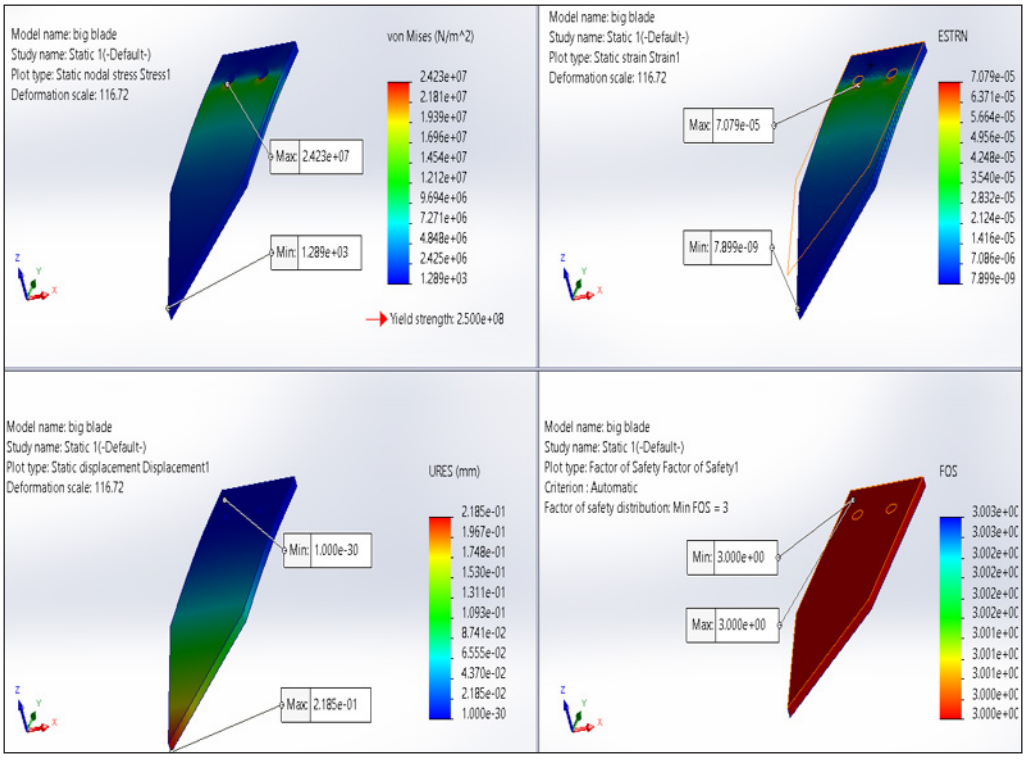


Figure 8. Big blade analysis utilising a force of 160 N for: (a) stress; (b) strain; (c) displacement; and (d) factor of safety

A safety factor of 1.0 indicates that the applied stress is equal to the material strength, and if the material is starting to deform at a specific location, there is no margin of safety (Burdekin, 2007). Figure 8 illustrates the distribution of the factor of safety, revealing that

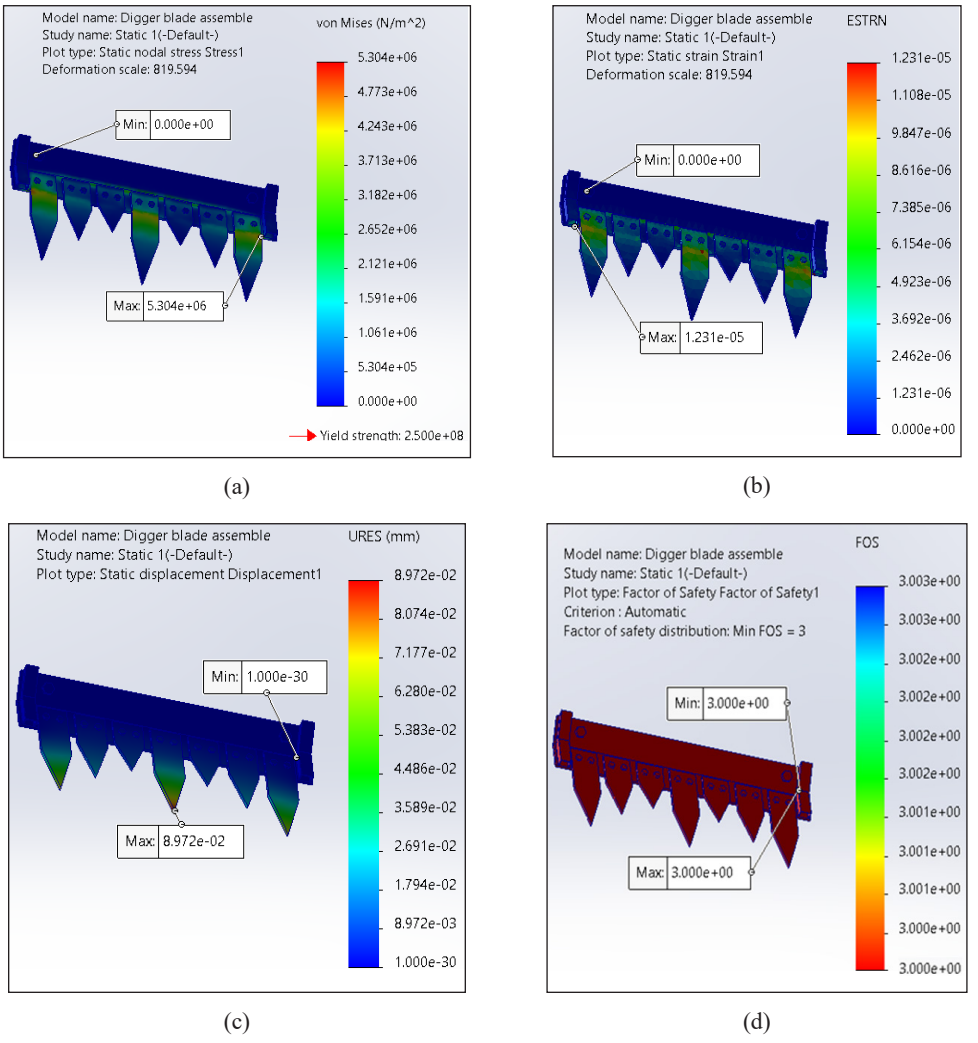


Figure 9. Digger blade analysis utilising a force of 400 N for: (a) stress; (b) strain; (c) displacement; and (d) factor of safety

the minimum factor of safety (FOS) recorded was 3. This shows that the material would begin to yield if the force is nearly tripled. The findings indicated that the yield strength of the big blade was 2.5×10^8 N/m^2, indicating that the big blade of the digging system will begin to deflect in the opposite direction when the strength exceeds this threshold (Figure 8). Miah et al. (2023) designed the furrow opener of a vegetable transplanter at FOS 1.9; however, for this digging blade, FOS was 3.0. This material commenced yielding when the von Mises stress neared the yield strength of 2.5×10^8 N/m^2. The maximum stress, strain, and displacement recorded were 2.423×10^6 N/m^2, 7.079×10^{-5}, and 0.2185 mm, respectively.

Conversely, the minimum stress, strain, and displacement were 1.289×10^4 N/m^2, 7.899×10^{-9} N/m^2, and 1.00×10^{-30} mm, respectively. The connection between the big

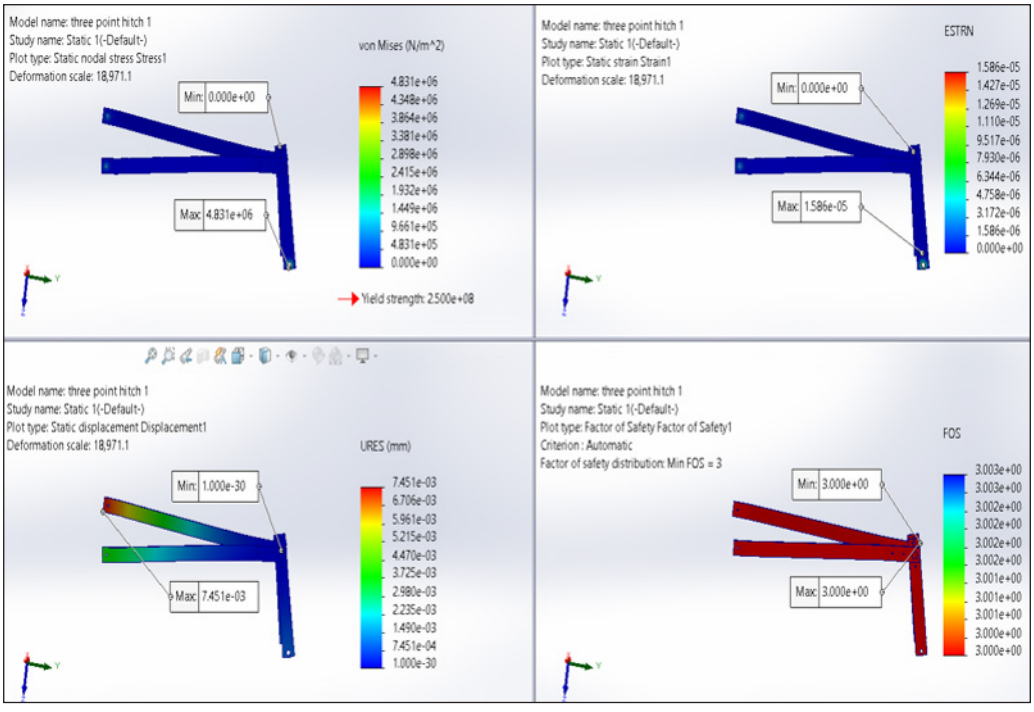


Figure 10. Three-point hitch analysis utilising a force of 400 N for (a) stress, (b) strain, (c) displacement, and (d) factor of safety

blade and the digger blade assembly was identified as the site of maximum stress and strain, which decreased progressively towards the front and rear sides. Furthermore, it was determined that the displacement was maximal near the tips of the large blades. It is important to operate the machine for at least 100 hours to find malfunctions in the different parts after fabrication (Miah et al., 2023). The developed lemongrass harvester was operated for a total period of about 100 hours over several testing days in multiple field performance evaluations conducted under normal field conditions. The machine did not undergo any systematic evaluation of durability or fatigue. During its operation, however, it was subjected to routine examination to determine the state of its main components. During the whole operating time, no substantial mechanical defects or malfunctions were found. The identical design analysis was likewise done to the digger blade assembly and the three-point hitch of the harvester, as depicted in Figures 9 and 10, respectively. Table 5 shows the results of the finite element investigation of the main structure components for the lemongrass harvester. Maximum stresses obtained in the large blade, digger blade assembly, and three-point hitch were well below the yield strength of ASTM A36 steel (2.50×10^8 N/m^2). Also, the maximum displacement was negligible, and the safety factor was 3 for all elements, indicating that the designed framework can successfully withstand the imposed stress conditions during harvesting.

Table 5
Finite element analysis results of different parts of the harvester

Component	Applied Load (N)	Maximum Stress (N/m^2)	Maximum Displacement (mm)	ASTM A36 Yield Strength (N/m^2)	Status
Big blade	160	2.42×10^{6}	2.19×10^{-1}	2.50×10^{8}	safe
Digger blade assembly	400	5.30×10^{6}	8.97×10^{-2}		safe
Three-point hitch	4000	4.83×10^{6}	7.45×10^{-3}		safe

Performance Test Results

Table 6 exhibits the effective field capacity (EFC), theoretical field capacity (TFC), and efficiency at various entry angles for the lemongrass harvesting machine. The machine underwent testing at two forward velocities (S1= 2 km/h and S2= 3 km/h) and three distinct entry angles (15º, 20º, and 30º). As the entry angle increases, the lemongrass harvesting equipment experiences higher resistance from the soil. The additional resistance comes from the machine's excavation or cutting activity at higher angles, necessitating greater energy to extract and elevate the lemongrass from the soil. As a result, the machine's efficiency is hindered, necessitating increased time and effort to cover the same area, hence diminishing its effective field capacity. The data indicates that the lemongrass harvesting machine operates most efficiently at an entry angle of 15° and a forward speed of 2 km/h, resulting in optimal field efficiency. This entry angle and forward speed allow the harvester to efficiently cover a substantial area while also making efficient use of its capacity. On the other hand, an entry angle 30º tends to result in the lowest EFC and field efficiency, making it a less favourable choice.

Field Performance at Entry Angle of 15º and Forward Speed of 2 km/h

The actual field performance of the tractor-operated lemongrass harvester and how efficient and precise the harvesting process of the harvester at an entry angle of 15º and a forward speed of 2 km/h is shown in Figure 11. Here, three graphs describe three important parameters of the harvester: successful harvesting, unharvested and damage percentage. The harvested yield remains consistently high and it is ranging from 80% to nearly 90%. This means that the harvester's performance is almost satisfactory, but there are still some challenges to improving the harvesting efficiency. On the other hand, lemongrass damage percentage was very low, indicating minimal injury occurred during harvesting. There were a few problems, such as undulation of the experimental field, varying root zone depth, and weed infestation. However, this pattern suggests that there is a need to optimise the design and control of the cutting depth and forward speed of the harvester.

Table 6
Field capacity and field efficiency at different entry angles and tractor forward speeds

Digger entry angle	Effective width (m)	Time required (h)		Theoretical field capacity (ha/h)		Effective field capacity (ha/h)		Efficiency (%)		Harvesting, %		Damage, %	
		S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
15°	0.73	0.014	0.014	0.147	0.221	0.065	0.067	44.52	30.27	85.61	81.35	5.81	8.96
20°	0.73	0.016	0.015	0.147	0.221	0.059	0.061	39.99	27.43	81.32	79.36	6.28	12.51
30°	0.73	0.016	0.016	0.147	0.221	0.056	0.058	37.96	26.36	76.57	68.24	10.37	15.24
Mean	0.73	0.015	0.015	0.147	0.221	0.060	0.062	40.82	28.02	81.17	76.32	7.49	12.24
SD	0	0.001	0.001	0.000	0.000	0.005	0.004	3.36	2.02	4.52	7.07	2.51	3.15
CV (%)	0	7.97	6.92	0.00	0.00	8.19	7.19	8.23	7.21	5.57	9.26	33.50	25.73
LSD (0.05)	-	*	*	-	-	*	*	*	*	*	*	*	*

*Significant at a 5% level of significance

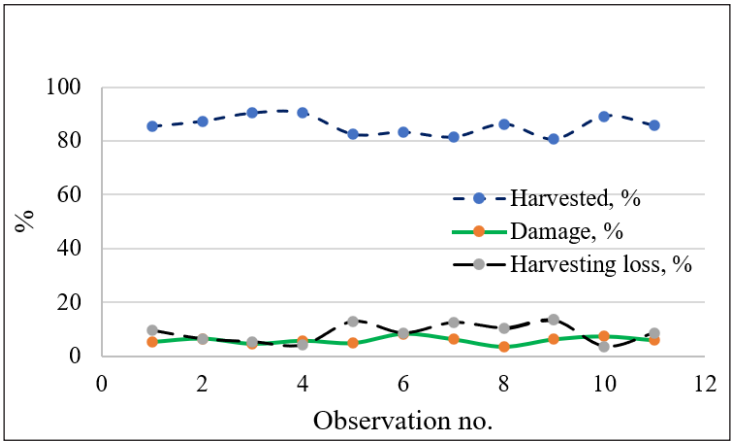


Figure 11. Field performance data of lemongrass harvester

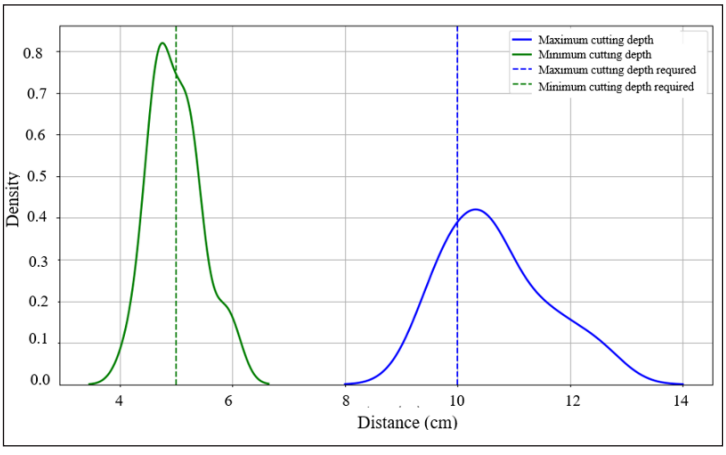


Figure 12. Lemongrass harvester cutting depth (minimum and maximum) uniformity

Minimum and Maximum Cutting Depth

Kernel density estimation (KDE) of the minimum and maximum cutting depths for a lemongrass harvester at an entry angle 15º and a forward speed of 2 km/h, showing the consistency of its cutting blade performance, can penetrate the root zone for uprooting lemongrass (Figure 12). The blue graph illustrates the distribution of maximum cutting depths. At the same time, the green curve indicates the minimum cutting depths observed during harvesting. Vertical dashed lines represent the theoretical maximum (blue) and minimum (green) cutting depths for reference purposes. It is important to know whether the cutting blade can reach up to the root zone or not. The figure shows that the density peaks for minimum cutting depth are more distinct and acute, centred at 4.8 cm. So, it is very close to the minimum cutting depth required for lemongrass uprooting.

The position of the effective rootzone of lemongrass in the soil subsurface is within 5 cm (Singh et al., 2000). The distribution of maximum cutting depth is wider and peaks at around 10.6 cm, and the required maximum cutting depth is 10 cm, which means there is no problem in terms of cutting depth. The divergence of both actual distributions from their corresponding required values indicates the developed machine can harvest lemongrass with minimal difficulty. The harvester attains consistently minimal cuts, although exhibits inconsistency at greater cutting depths. This analysis is essential for enhancing cutting methods and increasing operational efficiency.

Financial Analysis

The estimated cost to fabricate the lemongrass harvester in this project was USD 1,500. This value was used as the initial purchase cost for the financial analysis and considers an economic life of 12 years. Its typical annual use would be 720 h, assuming the bank interest is 10%, and the harvester's salvage value is 10% of the original price. Annual depreciation is calculated at USD 112.5 with a Capital Recovery Factor (CRF) of 0.147 (Table 7). The fixed cost includes capital consumption and shelter cost; if the machine did not operate for the whole year, this cost would be continuous and is USD 313.45 annually. At the same time, variable costs included fuel costs, operator wages, tractor hiring costs, and repair and maintenance costs. It depends on the machine's operating time. Here, the variable cost is USD 5690.80 annually. It was assumed that the charge for harvesting lemongrass using this harvester is USD 153/ha, and then the annual gross income reaches USD 7204.46. The benefit-cost ratio (BCR) and investment payback periods of the harvester are 1.20 and 1.25 years, respectively, indicating strong financial viability. The harvester BCR is low, and the payback period is very quick because the total cost (fixed and variable) is very high compared to gross income, but it would be profitable because the harvesting period is long (720 h/yr).

Break-Even Analysis

The break-even analysis graph shows the relationship between annual hours the harvester operates and the corresponding annual cost and returns. The X-axis represents the machine's operating hours, and the Y-axis represents the associated cost and return. There are two lines in the graph: the total cost line, which includes fixed and variable costs, and the return line, which indicates revenue from the lemongrass harvester. The break-even point is 150 hours, and the annual cost is USD 1500, where the two lines intersect (Figure 13). This means the harvester must operate at least 150 hours to cover all costs. It cannot be profitable if the machine operates below 150 hours annually. It will help the owner of the harvester to justify whether their investment will be profitable or not.

Table 7
Financial analysis of lemongrass harvester

Cost items	Estimated Value
Price of lemongrass harvester (USD)	1500
Economic life of harvester	12
Depreciation (USD/yr)	112.5
Capital Recovery Factor (CRF)	0.147
Fixed cost	
1. Capital consumption (CC), USD/yr	213.45
2. Shelter cost, USD/yr	100
Subtotal fixed cost, USD/yr	313.45
variable cost	
1. Effective operating time per day (h)	6
2. Average operation time per year (day)	120
Average operation time per year (h)	720
Fuel consumption per hour (L)	5
Diesel price in Malaysia, USD/L	0.51
Fuel cost USD/yr	1836
Repair and maintenance cost (USD/yr)	100
Operator cost in Malaysia (USD/day)	16.29
Operator cost (USD/yr)	1954.8
Tractor hiring cost in Malaysia (USD/day)	15
Tractor hiring cost (USD/yr)	1800
Variable cost (USD/yr)	**5690.8**
Total cost (USD. /yr)	**6004.25**
Field capacity (ha/h)	0.0654
Harvesting charge (USD/ha)	153
Gross income (USD/yr)	**7204.46**
Net income (USD/yr)	1200.21
Benefit cost ratio (BCR)	1.20
Payback period (yr)	1.25

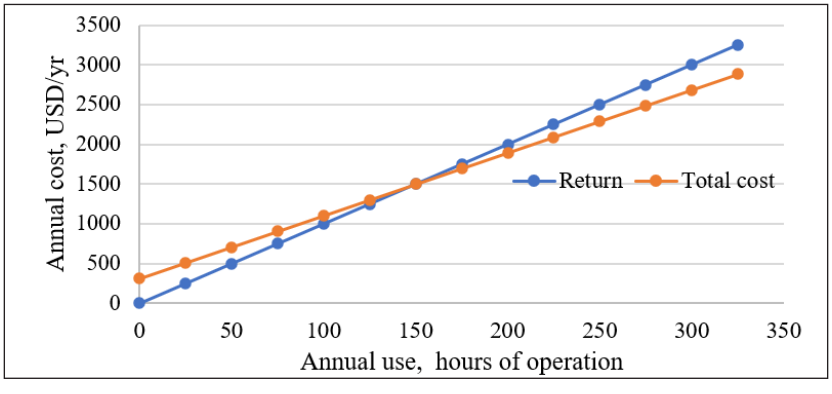


Figure 13. Break-even analysis of the lemongrass harvester

CONCLUSION

The development and evaluation of a tractor-mounted lemongrass harvesting machine showed high potential for harvesting lemongrass in a mechanised way. Through careful design and structural analysis of different parts, optimum performance was ensured with minimum harvesting loss or damage to the crop. The effective design of the V-shaped digger blade, rubber roller, supporting frame, and vibrating conveyor of the harvester ensured a desired uniform cutting depth and reliable uprooting. The blade entry angle of 15° at a forward speed of 2 km/h demonstrated the best harvesting outcomes. The harvester's economic analysis strongly supported its viability because the BCR is 1.20, and the payback period is just over one year. The field efficiency of the harvester is 45%, which means there are many challenges that need to be improved to increase the harvesting performance, such as enhancing harvesting efficiency and reducing crop damage. The lemongrass harvesting machine demonstrates potential as a practical and effective substitute for manual techniques. Its capacity to attain enhanced productivity, superior cutting precision, and less manpower demands renders it an attractive option for lemongrass harvesting operations. The harvester was developed for small to medium lemongrass producers, agricultural machinery manufacturers, and the regional lemongrass sector in Malaysia. The developed harvester was tested in particular agricultural field and crop-specific characteristics and its performance may vary due to different soil types, moisture levels and weather conditions. Additional research and development is recommended to enhance harvesting efficiency and reduce crop damage

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