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AFRICAN CENTER OF EXCELLENCE IN INTERNET OF THINGS (ACEIoT)

Designing and Implementing AI-Enhanced IoT Vermicomposting: Revolutionizing Waste Management with Tiny ML

A dissertation submitted in partial fulfillment of the requirements for the award of master of science degree in internet of things: wireless intelligent sensor network

Submitted By:

Name: KAYIRANGA Fabrice (Ref. No:218007081)

May, 2025

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Supervised by:

- Dr. James RWIGEMA
- Dr. Peace BAMURIGIRE

Ma, 2025

DECLARATION

I, Fabrice KAYIRANGA, a Master's student at the African Center of Excellence in Internet of Things, University of Rwanda, hereby declare that this research thesis is my own original work and has not been submitted previously for any other degree or professional qualification.

Signed: ______________________

Date: May /2025

BONAFIDE CERTIFICATE

This is to certify that the research work presented in this thesis is the original work of Fabrice KAYIRANGA (Ref. No.: 218007081), MSc. IoT student at the University of Rwanda, College of Science and Technology. It has been carried out under the supervision of:

Main Supervisor: Dr. James RWIGEMA. ………………………….

Supervisor: Dr. Peace BAMURIGIRE …………………………...

The Head of Masters Studies and Trainings,
Dr. James RWIGEMA

Signature: _______________ *Date:* _______________

DEDICATION

To my dear mother, whose love, sacrifices, and unwavering support have been my greatest strength. Your guidance and belief in me have shaped my journey.

To my family, for their constant encouragement, patience, and inspiration. Your support has been my foundation through every step of this journey.

With love and gratitude, I dedicate this work to you all

ACKNOWLEDGMENT

This research would not have been possible without the support, guidance, and contributions of several individuals and institutions. I would like to take this opportunity to express my deepest appreciation to all those who have played a role in the successful completion of this study.

First and foremost, I extend my heartfelt gratitude to my academic advisors and mentors, whose invaluable expertise, constructive feedback, and encouragement have been instrumental in shaping this research. Their continuous support, patience, and insightful guidance have greatly enriched my understanding of AI driven vermicomposting and sustainable agricultural practices.

I am immensely thankful to my colleagues, research collaborators, and fellow scholars who provided me with valuable discussions, suggestions, and technical insights that significantly enhanced the quality of this work. Their willingness to share knowledge and engage in thoughtful discussions has been a source of inspiration and motivation throughout this journey.

A special note of appreciation goes to the institutions and organizations that facilitated access to essential resources, research materials, and technological support. Their contributions enabled me to explore and implement innovative approaches in AI based vermicomposting, making this research more impactful and practical.

I am also deeply grateful to my family and friends for their unwavering support, encouragement, and patience during this journey. Their belief in my abilities and their constant motivation provided me with the strength to persevere through challenges and obstacles. Their presence has been a pillar of support, reminding me of the importance of dedication and resilience.

Furthermore, I extend my appreciation to the broader scientific community and professionals working in the fields of artificial intelligence, IoT, and sustainable agriculture. Their groundbreaking work has served as a foundation for this research, inspiring me to contribute to the ongoing efforts in environmental conservation and efficient waste management.

Lastly, I would like to acknowledge all the individuals, directly or indirectly, who have contributed to the realization of this research. Your support, encouragement, and contributions have been invaluable in making this project a success.

ABSTRACT

This research proposes an AI-based vermicomposting system that leverages the computational power of a Raspberry Pi to monitor and optimize the growth of *Eisenia fetida* (red wigglers) for high-quality organic fertilizer production in Rwanda. Traditional vermicomposting methods rely heavily on manual observation or multiple external sensors, which can be expensive and unsuitable for low-resource environments. To address this challenge, the proposed system replaces sensor-based monitoring with periodic image capture and advanced computer vision analysis.

A low-cost camera module integrated with the Raspberry Pi captures high-resolution images of the composting bin at regular intervals. These images are analyzed using Convolutional Neural Networks (CNNs) and other image processing techniques to assess worm health, developmental stage, and population density. Based on the visual data, the system provides actionable recommendations for manual interventions to maintain optimal composting conditions.

The research adopts a quantitative methodology, employing mathematical models for image classification and statistical methods to validate system performance. Designed for affordability and accessibility, the system utilizes locally available, energy-efficient components to ensure sustainability and ease of adoption. The outcomes of this research are expected to enhance vermicompost quality, promote sustainable agriculture, reduce organic waste, and support climate-resilient farming practices in Rwanda.

Keywords: *Vermicomposting, AI, Raspberry Pi, Computer Vision, Convolutional Neural Networks, Sustainable Agriculture, Rwanda.*

LIST OF ACRONYMS

ACEIoT: African Center of Excellence in Internet of Things

AI: Artificial Intelligence

ANN: Artificial Neural Network

API: Application Programming Interface

CNN: Convolutional Neural Network

CV: Computer Vision

GAN: Generative Adversarial Network

GPS: Global Positioning System

IoT: Internet of Things

ML: Machine Learning

NPK: Nitrogen, Phosphorus, and Potassium

Pi: Raspberry Pi

PWM: Pulse Width Modulation

RNN: Recurrent Neural Network

UI – User Interface

VCS – Vermicomposting System

WHS – Worm Health Status

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CHAPTER 1: GENERAL INTRODUCTION

1.0 Introduction

Rwanda's socioeconomic landscape is deeply intertwined with its agricultural sector, which not only sustains the livelihoods of more than 60% of its population but also contributes approximately 27% to the national Gross Domestic Product (GDP) [1]. Agriculture is the backbone of rural development in the country, underpinning food security, employment, and export earnings. However, the sector is increasingly challenged by the effects of climate change, soil degradation, population pressure on arable land, and unsustainable farming practices. In response, the Rwandan government and development partners have been encouraging the adoption of climate resilient and environmentally sustainable agricultural methods, chief among them being organic farming[2]

Organic agriculture emphasizes the use of biological inputs, natural soil fertility management, and avoidance of synthetic agrochemicals. Within this paradigm, vermicomposting the bio oxidation and stabilization of organic material through the joint action of earthworms and microorganisms—has emerged as a cornerstone technique [3]. Vermicomposting not only recycles agricultural and organic household waste but also enriches the soil with macro and micronutrients, improves its microbial composition, and enhances moisture retention. Earthworm species such as *Eisenia fetida*, commonly known as red wigglers, are preferred due to their rapid reproduction rate, voracious feeding habits, and resilience in decomposing organic substrates [4]. The result is a high quality compost that promotes soil health, enhances crop yields, and aligns with Rwanda's vision for green growth.

Despite these ecological and agronomic advantages, traditional vermicomposting methods face numerous operational inefficiencies, particularly in rural contexts where labor, technical knowledge, and monitoring tools are limited. Manual oversight of temperature, moisture, pH, and worm health is not only time-consuming but also error prone, leading to variability in compost quality and delays in production cycles [5] Additionally, subtle indicators of vermicomposting health—such as earthworm movement patterns, substrate color, or the emergence of pests are often missed without technical instrumentation. These limitations restrict scalability and discourage adoption among smallholder farmers who stand to benefit the most.

In the context of the Fourth Industrial Revolution, the convergence of Artificial Intelligence (AI), Internet of Things (IoT), and low cost embedded systems provides a compelling opportunity to modernize vermicomposting operations. Embedded microcontrollers and single board computers, such as the Raspberry Pi and ESP32, are now capable of integrating realtime sensor data with computer vision algorithms, offering new possibilities for intelligent agricultural monitoring [6]. AI based models, particularly in the domain of machine learning and deep learning, can be trained to detect worm health status, moisture levels, temperature anomalies, and compost maturity with high precision using image recognition and sensor fusion techniques [7].

The affordability, modularity, and scalability of such systems make them especially attractive for implementation in resource constrained rural environments. The integration of mobile applications and cloud connectivity further enables farmers to remotely monitor and manage their composting units, reducing dependency on labor and improving decision making. Moreover, Realtime feedback mechanisms can alert users to suboptimal conditions, promoting corrective actions before irreversible damage occurs [8].

This research proposes the design and implementation of a low cost, AI powered monitoring system tailored to the needs of smallholder farmers in Rwanda[9]. The system will leverage embedded hardware, multispectral sensors, and machine learning models to automatically track the key parameters of worm growth and compost quality[10]. By providing a Realtime, data driven approach to vermicomposting management, the project seeks to enhance compost consistency, improve agricultural productivity, and contribute to Rwanda's broader goals of sustainable agriculture and digital transformation[11], [12].

Ultimately, this research aims to bridge the technological gap between high impact environmental practices and accessible tools for the rural population[13]. The outcomes are expected to contribute not only to academic discourse in precision agriculture and AI applications but also to practical interventions aligned with Rwanda's National Strategy for Transformation and Vision 2050[5].

1.1 Background and Motivation

The global rise in organic waste generation, combined with increasing awareness of environmental sustainability, has prompted the need for innovative solutions in waste management—particularly in developing countries like Rwanda. Organic waste constitutes a significant portion of municipal and agricultural waste in Rwanda, yet much of it remains untreated or disposed of in landfills, contributing to greenhouse gas emissions and public health risks [6]. This challenge is especially pressing in rural and semiurban regions, where limited infrastructure and financial constraints hinder the adoption of advanced waste processing systems.

Vermicomposting, a biological process that uses earthworms to decompose organic waste into nutrient rich compost, has emerged as a sustainable alternative to conventional composting. Among various earthworm species, *Eisenia fetida* (red wigglers) are widely recognized for their high reproductive rate, tolerance to diverse substrates, and effectiveness in breaking down organic material [9]. Vermi cast, the end product of this process, is a valuable organic fertilizer that enhances soil fertility, promotes microbial activity, and improves water retention in agricultural soils [14].

Despite these advantages, traditional vermicomposting methods remain labor intensive, inconsistent, and difficult to scale, particularly in regions with fluctuating environmental conditions. Monitoring key factors such as substrate temperature, moisture content, and pH is essential to maintaining optimal conditions for worm health and compost quality. However, manual monitoring introduces delays, human error, and poor reproducibility, reducing overall efficiency and discouraging wider adoption [15].

To address these challenges, this research explores the integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies into vermicomposting systems. AI offers advanced capabilities for pattern recognition, anomaly detection, and predictive modeling, while IoT provides a framework for realtime sensing, remote monitoring, and data acquisition through low cost embedded systems [16]. The synergy between these technologies presents an opportunity to automate vermiculture management, enhance compost quality, and improve system responsiveness[15].

The research specifically focuses on designing and implementing an AI driven IoT system for monitoring and optimizing the vermicomposting process. The system employs environmental sensors (e.g., for temperature, humidity, and moisture) to continuously track conditions within the composting environment. Data is analyzed using machine learning algorithms capable of detecting suboptimal trends and triggering automated interventions—such as activating ventilation or hydration mechanisms—to maintain ideal conditions for *Eisenia fetida* [7][17].

The geographic and environmental scope of this research is centered on Rwanda, where smallholder farmers and peri urban communities often lack access to sustainable waste treatment options. By leveraging inexpensive, scalable technologies, this system is tailored to local conditions and resource constraints, offering a practical solution to organic waste management that also supports soil health and food security goals [8].

However, the study is deliberately scoped as a pilot scale implementation, focusing on proof of concept and technical feasibility rather than largescale deployment. It does not assess long term economic viability, environmental tradeoffs, or industrial scalability, which remain important topics for future investigation[18].

The anticipated outcomes of the study include:

- A functional prototype of a low cost, AI powered vermicomposting monitoring system.
- Demonstrated improvement in the rate of organic waste decomposition and quality of vermicast.
- A replicable framework that can be adapted to similar agricultural or community-
- based waste management settings across Rwanda and other developing regions.
- By aligning this research with Rwanda's national priorities in digital innovation and sustainable agriculture, the project aspires to bridge the gap between environmental sustainability and accessible technology, offering tangible benefits to both smallholder farmers and waste management initiatives

1.2 Problem Statement

Despite its benefits, traditional vermicomposting in Rwanda faces significant challenges. Current methods rely heavily on manual monitoring, which is prone to inconsistencies and human error. Inspections are infrequent, and the complex variables that influence the growth of Eisenia fetida—such as temperature, humidity, and moisture content are difficult to track effectively. This often results in suboptimal worm health and uneven compost quality, diminishing the overall effectiveness of the composting process.

Additionally, the high cost of advanced monitoring systems, which rely on sensors and automated control systems, prevents small scale farmers from adopting these technologies. Such systems are often too expensive for resource constrained farming communities in Rwanda. Therefore, there is a critical need for an affordable, scalable, and efficient solution that can monitor worm growth, health, and environmental conditions with minimal intervention[5].

This research aims to develop an AI based vermicomposting system that uses a Raspberry Pi and a camera module to monitor the health and growth of Eisenia fetida. By utilizing image processing techniques, the system will provide Realtime analysis of worm health, developmental stages, and population density, offering actionable insights to optimize the composting process—all without the need for costly sensors or complex automated alert systems.

1.3 Study Objective

1.3.1 General Objective

The central aim of this research is to design and implement an Ai driven vermicomposting monitoring system utilizing a Raspberry Pi integrated with a camera module. This system is intended to facilitate realtime observation and optimization of *Eisenia fetida* growth and health, ultimately enhancing the efficiency of organic fertilizer production processes in Rwanda.

1.3.2 Specific Objectives

The specific objectives of this research are outlined as follows:

1. To design and construct a system capable of capturing high resolution images of the vermicomposting environment at regular intervals.
2. To develop AI based computer vision algorithms capable of effectively analyzing the collected images to assess worm health, developmental stages, and population density.
3. To generate actionable recommendations derived from image analysis, enabling users to manually adjust environmental conditions to optimize the vermicomposting process.
4. To evaluate the system's overall performance by measuring improvements in compost quality, supported by technical metrics and statistical analyses that validate its effectiveness.

1.4 Hypothesis

1.4.1 Hypothesis 1:

The implementation of a custom designed image acquisition system will enable the consistent and high fidelity capture of vermicomposting environment data at predefined temporal intervals, with a system uptime and image clarity rate exceeding 95%.

1.4.2 Hypothesis 2:

Computer vision algorithms, trained on annotated image datasets, can achieve statistically significant accuracy (≥ 85%) in detecting key biological indicators such as worm health status, developmental stage, and population density, when compared to manual expert evaluations.

1.4.3 Hypothesis 3:

The actionable recommendations generated from image based analysis will lead to statistically measurable improvements in environmental control decisions (e.g., moisture, temperature, pH adjustments), thereby enhancing worm vitality and decomposition efficiency in the vermicomposting system.

1.4.4 Hypothesis 4:

The deployment of the proposed system will result in a statistically significant improvement in compost quality, measured by parameters such as nutrient content (NPK), organic matter degradation rate, and microbial activity, when compared to control groups utilizing conventional, non AI assisted vermicomposting methods ($p < 0.05$).

1.5 Significance of the Study

The significance of this study lies in its potential to revolutionize vermicomposting practices in Rwanda, enhancing both agricultural productivity and environmental sustainability. By integrating artificial intelligence (AI) and affordable embedded systems, the research offers a cost effective solution to optimize the growth of *Eisenia fetida* (red wigglers), improving organic fertilizer production. The AI based system provides realtime, data driven insights that allow small scale farmers to efficiently monitor worm health and composting conditions, thus addressing challenges related to soil fertility degradation and waste management. This innovation not only enhances the quality of compost but also contributes to sustainable agricultural practices by reducing reliance on chemical fertilizers, promoting nutrient recycling, and improving soil health. Additionally, the study's findings can be applied to other resource limited settings, offering a scalable solution to global challenges in waste management and sustainable farming. Ultimately, this research has the potential to improve food security, support sustainable development, and empower farmers in Rwanda and beyond.

1.6 Organization of the Study

This study is structured into five key chapters that guide the reader through the research process.

A. Chapter One presents the introduction, outlining the background of the study, the problem it seeks to address, the research objectives, the hypothesis, significance, scope, and potential impact.
B. Chapter Two reviews related literature, providing insights into previous work on vermicomposting, the use of Eisenia fetida in organic waste management, and the integration of Artificial Intelligence (AI) and Internet of Things (IoT) technologies in sustainable agriculture.
C. Chapter Three describes the research methodology, detailing the system design, hardware and software components, data collection techniques, and the AI models used for image analysis and environmental monitoring.
D. Chapter Four focuses on the implementation of the proposed system and evaluates its performance in real world conditions, analyzing the effectiveness of the AI based monitoring approach in enhancing worm health and compost quality.
E. Chapter Five summarizes the major findings, discusses the limitations of the study, and offers practical recommendations for future research and broader application. This structured approach ensures clarity and coherence throughout the study

1.7 Conclusion

In summary, this study seeks to address the limitations of traditional vermicomposting practices in Rwanda by introducing an AI driven, IoT enabled monitoring system. Through the integration of a Raspberry Pi and camera module, supported by computer vision algorithms, the system aims to provide realtime insights into worm health and composting conditions. The motivation for this research stems from the urgent need for cost effective and scalable technologies that can improve organic fertilizer production while minimizing manual effort and errors. The proposed solution not only enhances compost quality and agricultural productivity but also contributes to environmental sustainability by promoting efficient waste recycling. The following chapters will delve deeper into the theoretical foundations, system design, implementation process, and performance evaluation of this innovative approach to vermicomposting.

CHAPTER 2: LITERATURE REVIEW

2.0 Introduction

The integration of emerging technologies into sustainable agricultural practices has garnered significant attention in recent years, particularly in response to the global challenges of climate change, soil degradation, and inefficient waste management. Among the many sustainable solutions, vermicomposting the biological degradation of organic waste using earthworms—has gained prominence as a low cost, eco friendly method to enrich soil and recycle organic matter. It holds substantial potential for enhancing food security and soil fertility in low resource agricultural contexts such as Rwanda[19].

However, traditional vermicomposting systems are labor intensive and highly sensitive to environmental fluctuations, which can reduce efficiency and lead to inconsistent compost quality. These challenges are especially pronounced in rural and semiurban areas where technological resources and scientific training are limited. The literature suggests a growing interest in digital transformation of composting systems**,** particularly through the use of Internet of Things (IoT) devices and Artificial Intelligence (AI) to automate the monitoring and regulation of critical environmental parameters such as temperature, humidity, and moisture levels[20].

This chapter provides a comprehensive review of relevant literature concerning organic waste management, vermicomposting practices, and the application of AI and IoT technologies in agricultural systems. It begins by examining the role of organic waste and the limitations of conventional waste disposal techniques. It then explores the biological and agronomic foundations of vermicomposting and its contributions to sustainable farming[21]. The review continues by identifying the operational challenges in traditional vermiculture and evaluates existing technological interventions that have been proposed or implemented globally. Special attention is given to the feasibility and effectiveness of using computer vision and embedded AI for low cost monitoring in composting environments[20].

The purpose of this literature review is to identify knowledge gaps and technological limitations in existing vermicomposting systems, establish the theoretical basis for the proposed AI based solution. By synthesizing the current state of the art, this chapter lays the foundation for the design and development of an intelligent vermiculture monitoring system adapted to Rwanda's socioeconomic and environmental conditions[2].

2.1 Related works

2.1.1 AI Enabled IoT Based Vermicomposting Systems

Recent innovations in waste management have increasingly focused on integrating Artificial Intelligence (AI) and Internet of Things (IoT) technologies to optimize organic waste decomposition processes such as vermicomposting. Traditional vermicomposting, while environmentally friendly, often lacks the precision needed for consistent and high quality compost output. IoT enabled systems offer realtime monitoring of environmental parameters such as temperature, humidity, and moisture that are critical to the health and efficiency of *Eisenia fetida* (red wigglers), the primary composting agents in these systems[22].

Researchers like Kumar et al[23]. proposed a sensor based composting system that automates the collection of environmental data, helping users maintain optimal conditions and reduce manual oversight. Similarly, Singh and Prakash [15] demonstrated how machine learning models trained on environmental and biological data can predict worm activity levels and compost maturity, leading to better management decisions and higher quality outputs.

TinyML, which enables AI processing on microcontrollers with minimal power consumption, has opened new possibilities for deploying smart vermicomposting systems even in rural and offgrid settings. Using pretrained lightweight models, these systems can detect critical deviations from optimal composting conditions and trigger alerts or actuators (e.g., misting systems or fans) to restore balance[11].

Despite these advancements, challenges persist in achieving robust, cost effective deployments. Issues such as sensor calibration drift, power supply limitations, and data transmission failures can reduce system reliability. Additionally, many current models rely on small or synthetic datasets, limiting their generalizability across varied composting environments[21].

Nevertheless, Ai enhanced vermicomposting systems continue to gain traction for their potential to transform waste management practices, especially in agriculture heavy regions. These systems not only reduce organic waste but also promote sustainable farming by producing nutrient rich compost efficiently and with minimal human intervention[24].

2.1.2 Integration of IoT and Computer Vision in Agriculture

The advancement of Internet of Things (IoT) and computer vision technologies has significantly impacted the agricultural sector. Applications include crop disease detection, pest management, yield prediction, and livestock monitoring [3]. Computer vision systems, particularly those powered by Convolutional Neural Networks (CNNs), are highly effective in analyzing visual data and can be trained to detect patterns and anomalies in agricultural environments. [4].

2.1.3 Application of Raspberry Pi in Agricultural Systems

The Raspberry Pi is a powerful, low cost single board computer widely adopted in agricultural IoT systems due to its compatibility with various sensors and cameras, compact size, and affordability [5]. With support for open source frameworks like OpenCV for image processing and TensorFlow for machine learning, it is ideal for edge computing tasks in field environments[21].

In precision agriculture, Raspberry Pi has been used for soil moisture monitoring, pest detection, and automated irrigation. Its ability to perform local data processing and then upload summarized results to cloud platforms makes it suitable for low bandwidth rural deployments.

In this research, Raspberry Pi will serve as the core computational unit for the proposed system. It will capture realtime images using an attached camera, process these images locally using trained CNN models, and log key insights into a remote dashboard. This setup eliminates the need for multiple physical sensors, making the system both scalable and affordable for smallholder farmers[25].

2.1.4 AI and Machine Learning for Optimization in Vermicomposting

AI and machine learning are increasingly used to optimize vermicomposting by automating monitoring, detecting anomalies, and predicting composting stages. Supervised learning helps classify compost maturity, while time series models forecast environmental changes. Clustering reveals patterns in waste inputs, and reinforcement learning enables adaptive control of conditions. Techniques like TinyML and synthetic data generation allow deployment in low resource settings. Overall, AI improves compost quality, system efficiency, and scalability in sustainable waste management[26].

2.2 Review of Existing Studies and Limitations

TABLE 1: VERMICOMPOSTING SUSTAINABLE APPROACH

Author	**Title**	**description**	**gap**
[1] E. Kayabasi and A. Yilmaz	Vermicomposting: Sustainable Approach for Organic Waste Management	Explores the role of vermicomposting in organic farming and soil health.	Lacks integration of technology in vermicomposting systems.
[2] J. Sharma and S. Kumar	Organic Farming and Vermiculture	Discusses small scale challenges in vermiculture practices.	Does not propose affordable automation or realtime monitoring.
[3] S. Arya and R. Kala	Applications of Deep Learning in Precision Agriculture	Reviews deep learning in agriculture including CNN based monitoring.	No application to composting or worm based systems.
[4] L. Smith	CNNs for Image Analysis in Agriculture	Describes CNN use in classifying plant and soil features.	Focuses on plant imagery; no application to compost ecosystems.
[5] M. Amin	Developing IoT Applications Using Raspberry Pi	Demonstrates lowcost IoT solutions using Raspberry Pi.	Does not integrate camera based monitoring for worm environments.
[6] R. Patel	Smart Composting Systems	Reviews smart composting efforts and sensor use.	Lacks focus on imagebased analysis or lowcost vision systems.

2.3 **G**aps in Existing Research

While computer vision and IoT are increasingly applied in modern agriculture, their use in composting, particularly vermicomposting, remains limited. Existing smart composting systems often rely on multiple sensors to monitor parameters such as temperature, gas emissions, and moisture content. These solutions are typically costly, complex, and energy intensive, limiting their adoption by smallholder farmers in developing countries[14].

There is a notable research gap in developing affordable, image based systems that can monitor composting conditions without physical sensors. Current literature focuses either on sensor based monitoring or computer vision in crops, neglecting compost ecosystems and worm environments.

This study aims to bridge that gap by introducing a novel, image only monitoring solution using Raspberry Pi and CNN models. By capturing and analyzing visual data from the vermicomposting environment, the system can infer worm activity and compost quality in realtime, offering a low cost, noninvasive alternative suitable for widespread deployment in lowresource settings[17].

2.4 Novelty

This research introduces a novel approach to optimizing vermicomposting by integrating computer vision based Artificial Intelligence (AI) with low cost embedded Internet of Things (IoT) systems. While traditional vermicomposting monitoring relies on physical sensors to measure environmental parameters such as temperature, moisture, and humidity, this study proposes an image based solution that significantly reduces hardware complexity and cost. By analyzing visual data captured from compost beds, the system is designed to infer key composting conditions—such as worm activity levels and substrate moisture—through lightweight AI models trained for this purpose.

What distinguishes this work is its focus on developing a fully autonomous, edge based solution that does not depend on cloud infrastructure. The system is implemented on affordable embedded platforms such as Raspberry Pi or ESP32CAM, enabling realtime data processing and decision making directly at the site of deployment. This is particularly important in rural or semiurban regions of Rwanda, where internet connectivity and access to advanced technical support are often limited. The model is trained to operate with minimal power requirements and is designed to be user friendly and maintainable by individuals without advanced technical expertise.

Moreover, this research addresses a key gap in the existing literature and technological solutions by tailoring its approach to the socioeconomic realities of smallholder farmers in developing countries. Most existing systems either target industrial scale composting or rely on expensive sensor networks and cloud based analytics. In contrast, this study presents a cost effective, scalable, and field adapted solution that can significantly improve compost quality, reduce worm mortality, and contribute to sustainable agriculture through efficient organic waste management.

To the best of the researcher's knowledge, this is the first study to propose an image driven, embedded AI system for vermicomposting tailored specifically for lowresource settings. Its novelty lies in the convergence of sustainable agriculture, affordable technology, and localized design, offering a practical and innovative alternative to existing vermiculture monitoring systems.

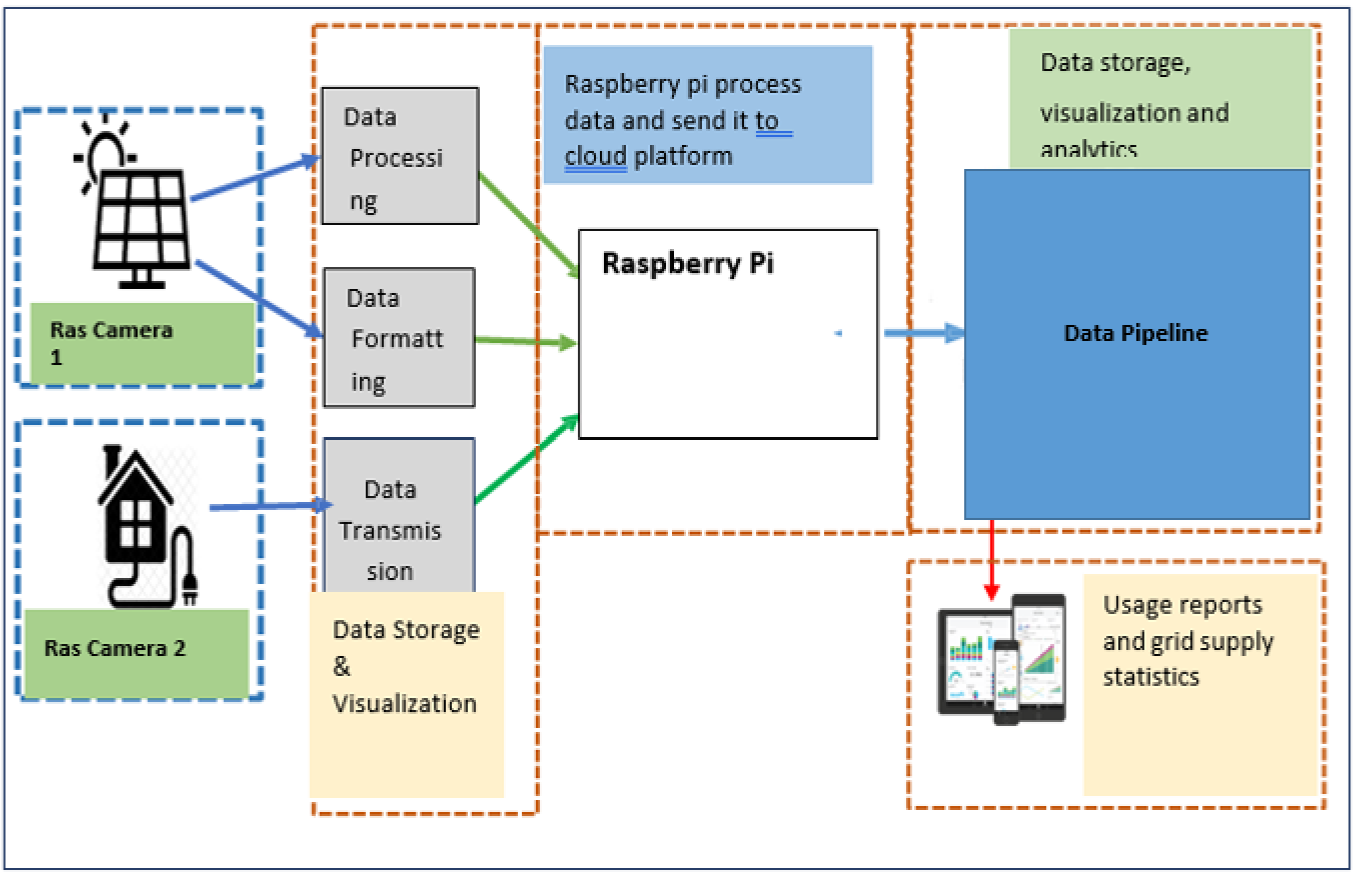


FIGURE 1:SYSTEM ARCHITECTURE

CHAPTER 3: RESEARCH METHODOLOGY

3.0 Methodology

The AI Enhanced IoT Vermicomposting System is designed to integrate an NPK sensor with a Raspberry Pi platform to measure the nutrient content of compost, specifically nitrogen (N), phosphorus (P), and potassium (K) levels. This data provides critical insights into the fertilization potential of the compost. Realtime readings from the NPK sensor will be processed and analyzed by machine learning models deployed on the Raspberry Pi, enabling the assessment of worm health, compost quality, and overall system efficiency. The system will continuously observe worm activity, compost consistency, and nutrient dynamics, transmitting the collected data to a central server over the Internet for realtime analysis and automated decision support. This intelligent feedback mechanism will support dynamic adjustments to maintain optimal conditions for the worms and ensure the production of high quality compost. The research methodology includes identifying the necessary hardware and software components, developing a functional prototype through the integration of the NPK sensor and the Raspberry Pi, and implementing machine learning algorithms for realtime data interpretation. Rigorous testing will be conducted to validate system performance, and IoT platforms will be utilized to support realtime analytics and data visualization, fostering continuous optimization of the vermiculture process.

3.1 Research Design

This research adopts a design science methodology to develop a functional prototype for monitoring vermicomposting processes using an AI based embedded system. The prototype focuses on realtime image acquisition, processing, and analysis to assess worm health and compost conditions without relying on additional environmental sensors. To complement the visual data, an NPK sensor is integrated into the system to measure the nutrient content of the compost—specifically nitrogen (N), phosphorus (P), and potassium (K) levels—providing critical insights into the fertilization potential of the end product. The system is intended to be low cost, scalable, and accessible for smallholder farmers in resource constrained environments. Design science methodology emphasizes the creation and evaluation of artifacts intended to solve identified problems [1]. In this study, the artifact is a computer vision and sensor based monitoring system utilizing a Raspberry Pi platform. The research process involves iterative cycles of system design, implementation, and evaluation to ensure the system meets practical requirements for vermicomposting monitoring and nutrient analysis.

3.3 Population and Sampling

The study focused on the use of AI Io enabled vermicomposting systems in Rwanda. A convenience sampling method was employed, targeting farms or waste management sites that are implementing organic waste composting using worms. A total of 5 active vermicomposting sites were selected for data collection, each utilizing a combination of sensors and image based monitoring systems.

A. **Target Population:** Vermicomposting sites in Rwanda using AI IoT systems or traditional methods.
B. **Sampling Method:** Convenience sampling, targeting accessible sites.
C. **Sample Size:** 5 vermicomposting sites.

This sample size was considered adequate for the exploratory analysis of the system's performance, challenges, and the feasibility of deploying AI driven monitoring in low resource settings

3.4 System Development Approach

The system development process began with identifying the need for realtime, low cost monitoring of worm health and compost conditions. The design integrated a Raspberry Pi, camera module, NPK sensor for nutrient monitoring, and AI driven image analysis using convolutional neural networks (CNNs). A prototype was developed using these components, followed by testing and validation to ensure optimal performance in real world vermicomposting environments.

3.5 Model Development

The system development process began with requirement analysis, where the key challenges in vermicomposting monitoring were identified, particularly the need for realtime, low cost, and accurate observation of worm health and compost conditions. The system design phase involved developing a comprehensive hardware and software architecture that integrates various sensors and technologies to monitor and analyze the composting environment.

The components of the system include:

A. **Raspberry Pi:** Acts as the central processing unit for collecting and analyzing data.

B. **Camera Module:** Captures visual data for AI driven image analysis, used to assess worm activity and compost quality.

C. **NPK Sensor:** Measures the nitrogen (N), phosphorus (P), and potassium (K) levels in the compost, essential for evaluating nutrient content.

D. **AI Driven Image Analysis:** Uses convolutional neural networks (CNNs) to interpret the visual data from the camera and provide insights into compost quality and worm health.

After the design was completed, a prototype was developed using the selected hardware components and software tools, implementing the planned architecture. Finally, the system was tested and validated through experiments to assess its performance in practical vermicomposting environments. This structured approach ensured that each phase of development addressed specific objectives and maintained alignment with the project's overall goals.

3.6 Machine Learning Model Training and Application

Machine learning (ML) techniques were integrated into the system to enhance its intelligence by enabling predictive analytics, anomaly detection, and insights into composting processes, such as worm health and compost quality.

Preprocessing Steps:

A. **Data Cleaning:** Removal of duplicates and correction of inconsistencies in sensor and visual data to ensure accurate input for the machine learning model.

B. **Normalization:** Feature scaling of environmental and compost related data (such as NPK levels and visual data) to improve model convergence and performance.

C. **Feature Selection:** Identifying relevant variables like NPK levels, worm activity patterns, compost quality, and environmental conditions to enhance model prediction accuracy.

Dataset Split:

To evaluate model performance, the dataset was divided into two parts:

- **80% Training:** This portion of the data was used to train the machine learning models, allowing them to learn patterns and relationships from the data.

- **20% Testing:** The remaining 20% was reserved for testing, to assess the model's performance on unseen data. This ensures a reliable and unbiased evaluation of prediction accuracy and the model's ability to generalize to new, real world data.

This preprocessing and dataset splitting steps ensure that the machine learning models are both trained effectively and evaluated impartially.

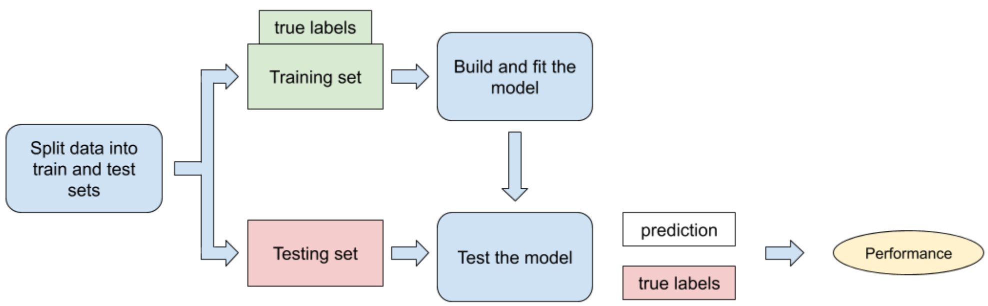


FIGURE 2:EMBEDDED SYSTEM BLOCK DIAGRAM

3.6 Language Development and Integration

The development of the AI enhanced vermicomposting system involved a layered integration of programming languages and tools, each supporting a specific aspect of system operation. This ensured seamless communication between sensors, computing devices, and the user interface for realtime data analysis and decision making.

3.7 User Interface Development

The frontend of the system was developed using HTML and CSS, delivering a user friendly web based dashboard for displaying compost metrics such as temperature, moisture, and worm activity. This interface enables users to monitor the vermicomposting environment, track progress, and receive alerts on anomalies or compost maturity.

3.7 1 Server-Side Logic

The backend was built using Python, which handled the system's core logic, including sensor data processing, machine learning model inference, and API development. Python scripts collected data from sensors, analyzed images from camera feeds, and evaluated composting conditions, enabling intelligent feedback and predictive insights.

3.7.2 Real Time Hardware Communication

A Raspberry Pi served as the central processing unit, facilitating realtime communication with camera modules and fertilizer (NPK) sensors. It handled data acquisition, preprocessing, and transmission to the backend. This setup ensured reliable environmental monitoring, enabling accurate detection of worm behavior, nutrient levels, and compost condition.

Integrated Language Stack Overview

A. **Frontend**: HTML and CSS for layout design and dashboard display
B. **Backend**: Python for server side logic, sensor data handling, and AI model integration
C. **Hardware Control**: Raspberry Pi interfacing with camera and sensor modules for realtime monitoring

CHAPTER 4: SYSTEM DESIGN AND DEVELOPMENTS

The integration of IoT and AI technologies is essential for creating intelligent systems that enhance efficiency, accuracy, and user convenience. This chapter outlines the analysis and design of an IoTBased Vermicomposting Monitoring System**,** detailing its architecture, functional requirements, and workflow.

4.1 System Block Diagram

This block diagram illustrates the architecture of the system designed to optimize and automate the vermicomposting process. By integrating diverse technologies, the system addresses critical challenges in traditional composting methods and provides a seamless, cost effective, and efficient monitoring solution.

4.1.1 Addressing Existing Problems:

a. **Inefficient Monitoring Methods:** Traditional vermicomposting methods rely on manual monitoring, which can be time consuming, inaccurate, and inconsistent. Our system addresses this by using IoT enabled NPK sensors and image based monitoring through Raspberry Pi and camera modules, providing realtime, noninvasive observations of the composting process, ensuring more accurate data collection and faster feedback.

b. **Lack of Real Time Data and Monitoring:** Many composting systems do not provide realtime data, which makes it difficult to make quick adjustments when the composting conditions are not optimal. Our system integrates cloud connectivity using WiFi modules, enabling realtime access to composting data. This allows for efficient decision making and better management of the composting process.

c. **Limited Automation and Precision:** Traditional methods often lack the necessary automation and precision for optimal composting. By incorporating AI driven image analysis (using Convolutional Neural Networks, CNNs), our system automates the assessment of compost quality, worm activity, and environmental conditions, ensuring high quality compost and efficient worm management.

d. **Inadequate Anomaly Detection:** Manual monitoring can miss anomalies such as improper temperature, moisture levels, or worm activity, which can negatively impact compost quality. Our system integrates machine learning algorithms to automatically detect anomalies, sending realtime alerts and enabling corrective actions to improve compost health.

e. **High Costs and Complexity for Smallholder Farmers:** Existing systems for monitoring composting conditions are often costly and complex, limiting their adoption by smallholder farmers. Our system uses affordable hardware such as Raspberry Pi**,** camera modules**,** and NPK sensors, alongside open source software, making it a low cost and easy to use solution tailored for smallholder farmers in low resource settings.

4.1.2 Vermicomposting System Three Layered Architecture

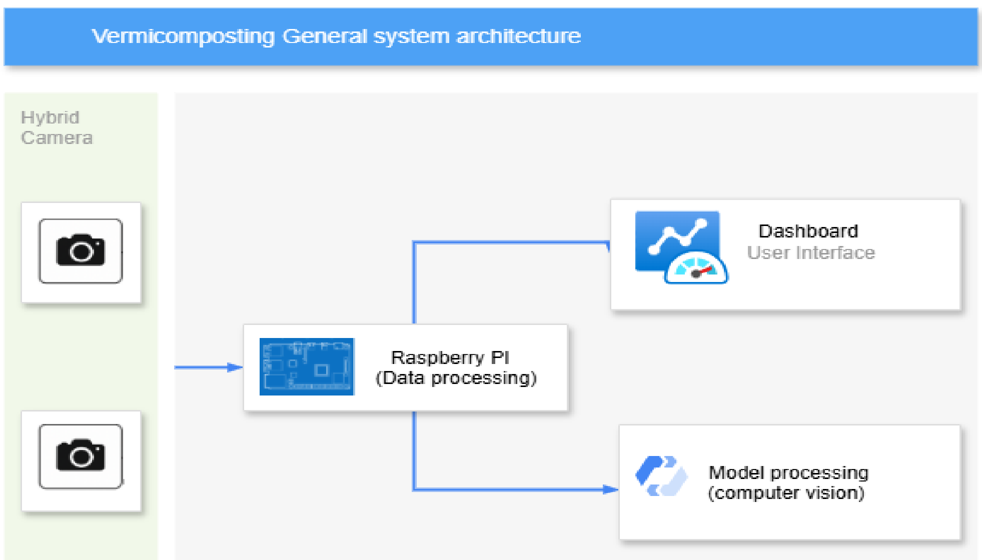


FIGURE 3 GENERAL SYSTEM ARCHITECTURE

4.2 Uniqueness of the System

A. **Integrated AI IoT Approach:** The seamless integration of IoT devices (such as NPK sensors, camera modules, and Raspberry Pi) with machine learning algorithms sets our system apart. This combination enables intelligent data collection, processing, and realtime decision making, optimizing compost quality and worm health monitoring.

B. Comprehensive Data Management: The use of cloud storage and SQL databases allows for robust and secure management of composting data. Administrators can easily access historical data, generate insightful reports, and optimize composting conditions based on realtime analysis, improving both system performance and efficiency.

C. **Real Time Remote Control and Monitoring:** The system's web dashboard provides administrators with remote access to system data, enabling real time monitoring and control of vermicomposting conditions. This feature facilitates immediate response to issues such as temperature fluctuations or moisture imbalance and allows for proactive maintenance to ensure optimal composting conditions.

D. **Enhanced User Experience:** The integration of AI driven image analysis alongside sensors for temperature, moisture, and NPK levels enhances the system's ability to assess compost quality accurately. This provides a user-friendly interface with actionable insights for compost management, improving the overall user experience for farmers and compost managers.

E. **Low Cost and Efficient Monitoring:** Our system uses low cost hardware such as Raspberry Pi and camera modules integrated with sensors for realtime monitoring of the compost environment. The system's affordability and efficiency make it suitable for smallholder farmers and other users in low resource settings.

TABLE 2 :PROTOTYPE PIN CONNECTION FOR VERMICOMPOSTING

COMPONENT	CONNECTION
CAMERA 1	Connected to the Camera Module interface on Raspberry Pi
CAMERA 2	Connected to a USB port on Raspberry Pi
RASPBERRY PI	Handles data processing and cloud communication
POWER SUPPLY	External power supply for Raspberry Pi
GSM SIM900	**GND**: Connected to **GND** of Raspberry Pi **TX**: Connected to **GPIO 2** (Pin 3) of Raspberry Pi **RX**: Connected to **GPIO 3** (Pin 5) of Raspberry Pi
NPK SOIL SENSOR	Interface Compatibility: Connects to Raspberry Pi via GPIO or USB to serial adapter
CLOUD CONNECTION	Data transmitted to the cloud via GSM module

The flowchart outlines the workflow of the IoT based vermicomposting system, starting with the system capturing an image to assess compost conditions. If the data meets predefined conditions, monitoring continues; otherwise, alerts are sent for issues like out of range parameters or sensor failures. The system ensures validation at each step, offering realtime feedback and logging data for continuous optimization of composting conditions.

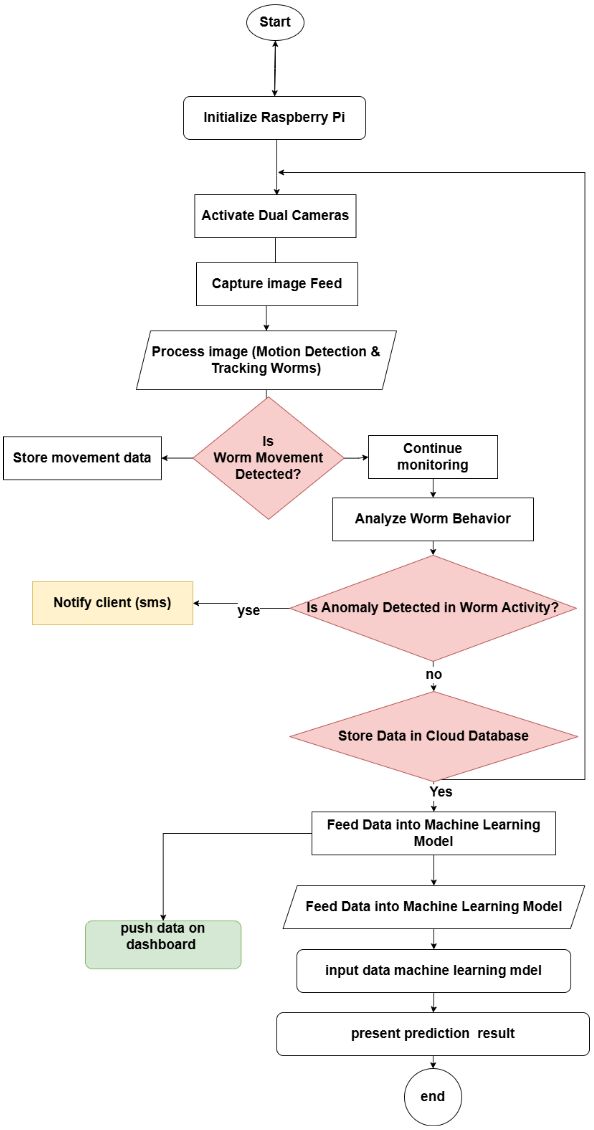


FIGURE 4:GENERAL SYSTEM ARCHITECTURE

4.3 Hardware connection for vermicomposting

The vermicomposting system integrates several components for efficient monitoring. A Raspberry Pi serves as the central unit, connected to a camera module and NPK sensors to track the compost environment. These sensors communicate through GPIO pins for realtime data collection. The system is powered by a regulated DC supply and uses WiFi modules for cloud communication, enabling remote access. A display module provides onsite status updates for easy user interaction

FIGURE 5 VERMICOMPOSTING PROTOTYPE

The IoT based vermicomposting system integrates an NPK sensor, camera, and Raspberry Pi to monitor and optimize the composting process. The Raspberry Pi serves as the central processing unit, controlling and coordinating the data flow from the NPK sensor and camera. The NPK sensor measures the nitrogen, phosphorus, and potassium levels in the compost, providing realtime data on compost quality. The camera captures visual data, which is analyzed using machine learning models to assess worm activity and compost conditions. The system uses cloud connectivity to allow remote monitoring and control. Power is supplied through a regulated DC source to ensure stable operation of all components. This system provides a cost effective, noninvasive, and efficient solution for monitoring vermicomposting, with the ability to optimize compost quality based on realtime data analysis.

CHAPTER 5: RESULTS AND ANALYSIS

5.0 Introduction

This chapter presents the findings from the implementation of an AI enhanced IoT based vermicomposting monitoring system. It focuses on evaluating the system's performance in tracking worm activity, monitoring compost health, and supporting informed decision making. Quantitative data was collected through observational analysis and recorded metrics such as micromovements, total movement, and NPK sensor readings. These inputs were used to validate the effectiveness of realtime camera analysis and AI predictions in managing organic waste.

5.1 Compost Activity Evaluation

The system successfully tracked worm activity and monitored composting stages using two camera modules and AI based image analysis. The system classified compost progress through image recognition of worm behavior and visual changes in substrate texture and color. Two metrics were recorded:

A. **Micromovement**: Small, localized worm shifts.
B. **Total movement**: Broader worm activity throughout the composting area.

These indicators provided insights into compost development stages, allowing evaluation without relying solely on environmental sensors.

5.2 System Testing and Functional Validation

The results are categorized into three key sections:

A. **Compost Activity Evaluation**
This section summarizes the data collected on the behavior and movement patterns of worms under different environmental conditions, providing insights into compost activity.

B. **System Testing and Validation**
Here, the integration of the Raspberry Pi, camera feed, and NPK sensors is reviewed to ensure consistent and reliable monitoring of the vermiculture process.

C. **AI Model Performance**
This section evaluates the accuracy and reliability of the AI model in detecting anomalies and assessing the maturity of the compost, ensuring it meets the intended goals for automation and monitoring.

5.2.1 Website Performance and Functionality

The system's functionality was thoroughly evaluated to confirm effective integration of AI and IoT components. The Raspberry Pi successfully managed input from NPK sensors and camera modules, enabling realtime monitoring of compost conditions. The AI powered image analysis provided accurate insights into compost quality, while the web dashboard allowed users and administrators to view data, receive recommendations, and manage processes remotely. Data was stored in the cloud for continuous access and analysis, supporting informed decision making and enhancing composting efficiency without relying on traditional moisture sensors.

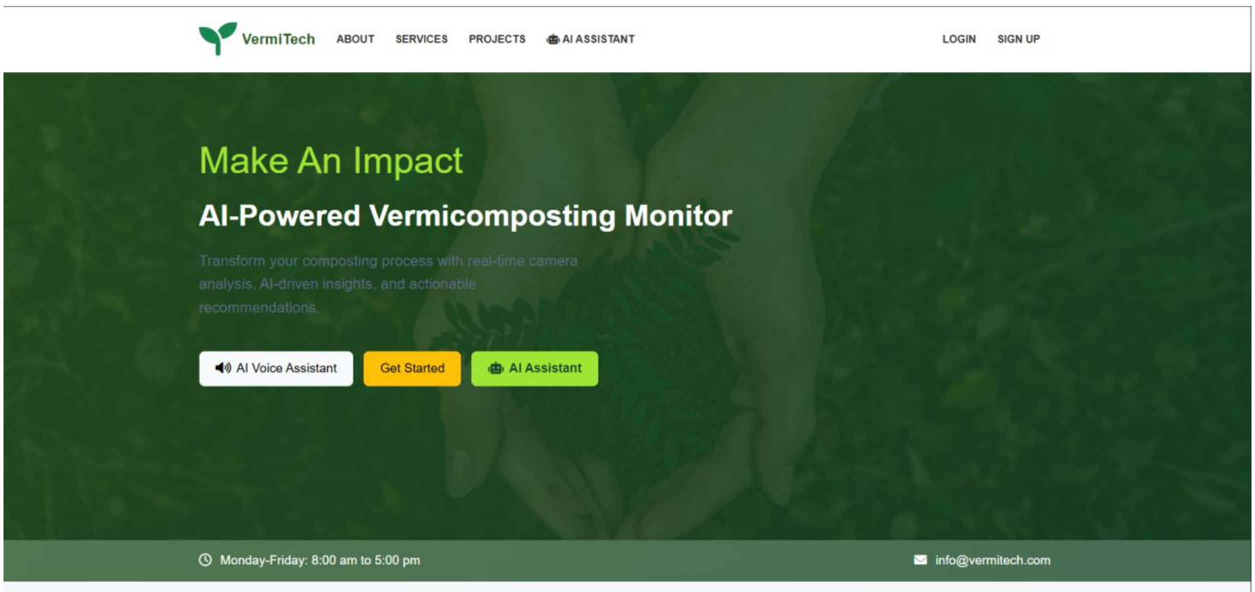


FIGURE 6: WEBSITE DESIGN OF VERMICOMPOSTING

5.3 Accuracy and Classification Performance

5.3.1 Accuracy

The Classification Report Metrics chart compares precision, recall, and F1score for a binary classifier used in the vermicomposting system, evaluating the detection of two classes: healthy compost and degraded compost. The balanced values for each class demonstrate consistent classifier performance, with a noticeable higher accuracy in detecting healthy compost instances compared to degraded compost.

To understand the factors influencing compost quality, we analyzed the distribution of compost types (e.g., healthy, partially degraded, and degraded). The graph reveals a roughly equal distribution of healthy, partially degraded, and degraded compost, with each category representing a comparable portion of the total compost samples.

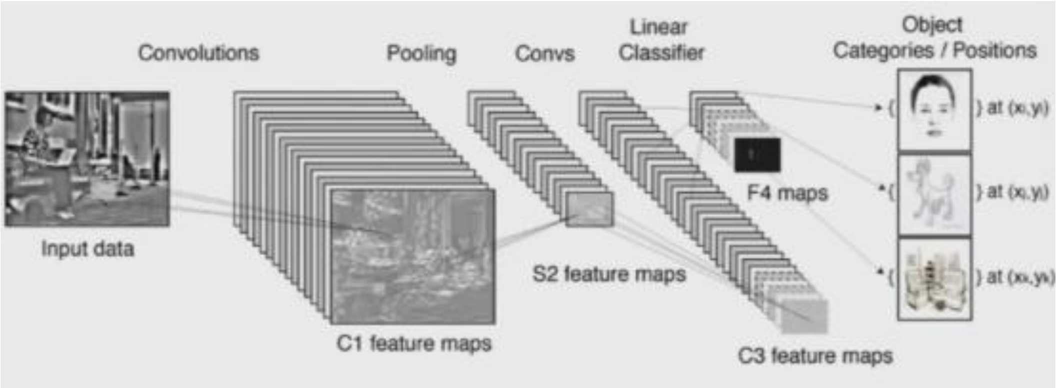


FIGURE 7:EXAMPLE OF A CNN ARCHITECTURE FOR OBJECT CLASSIFICATION

The image above illustrates the architecture of a Convolutional Neural Network (CNN), which we used to monitor and analyze the vermicomposting process. It begins with input images captured from a camera placed above the composting unit. These images include visual data on worm movement, compost texture, and moisture conditions. The first convolutional layers apply learnable filters to detect key features such as worm outlines, organic matter distribution, and structural patterns in the compost. Pooling layers follow to reduce the dimensional size of the feature maps, making the model more efficient and less sensitive to slight shifts in the input—like changes in worm position or camera angle.

Further convolutional layers in our model extract more complex features, such as clusters of worms (indicating healthy activity), uneven compost surfaces, or potential signs of degradation. These processed features are then passed to a linear classifier that evaluates the compost's health status—categorized as healthy, partially degraded, or degraded and also classifies worm activity levels. The final output of the CNN not only provides these classifications but also localizes specific areas within the compost pile that may require human or automated intervention. This approach allowed us to automate the observation process, making vermicomposting more efficient, scalable, and responsive to environmental change.

5.4 Results Obtained

The vermicomposting prototype successfully monitored the composting process through realtime visual data collection and analysis. The camera captured high quality images which were used by the AI model to assess worm activity and compost development over time. The system accurately identified different composting stages based on color changes, worm movement density, and visible decomposition patterns. These results were presented on an LCD display and through a remote dashboard interface.

The visual based monitoring approach proved effective in classifying composting stages without relying on traditional environmental sensors. The integration of AI and IoT in this system enabled timely decision making, such as when to intervene, feed the worms, or harvest the compost, thereby validating the objective of building a smart, sustainable vermicomposting

solution.

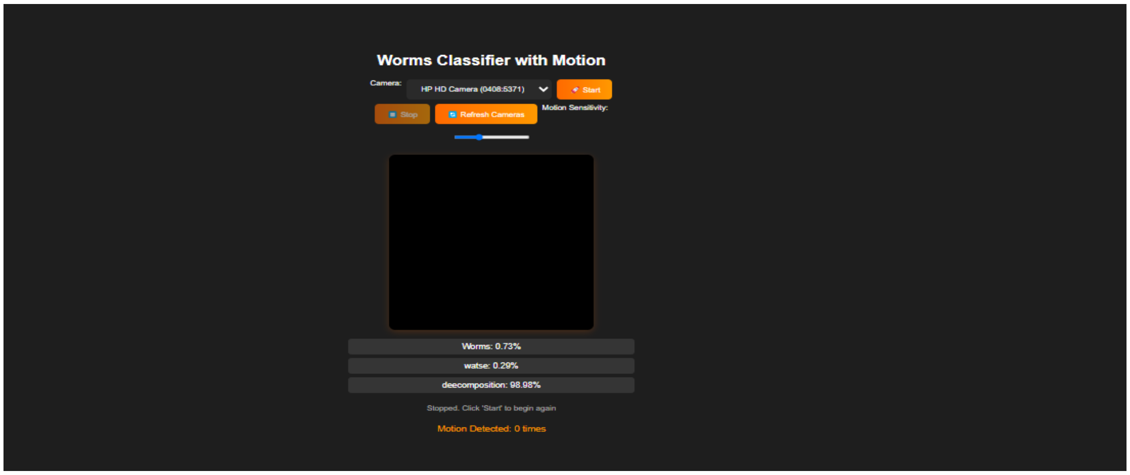
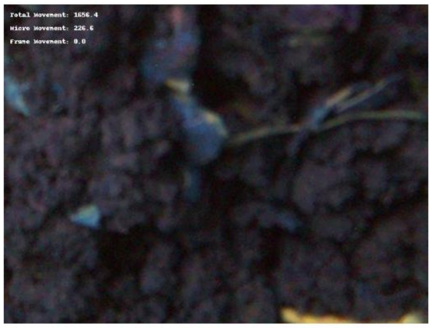


FIGURE 9 :CAMERA 2 IMAGE RESULT

Motion Tracking Dashboard

Live Feed



Movement Statistics

Metric	Value
Tracked Objects	0
Motion Status	None
Total Movement	1656.42
Micro-movement	226.58

FIGURE 10:STARTING WEBSERVER

The Motion Tracking Dashboard provides realtime insights into activity within the vermicomposting environment using camera based monitoring. The live feed displays the composting area while overlayed metrics track key movement indicators such as total movement (1656.42) and micromovement (226.6), which reflect subtle worm activity. Despite no tracked objects or active motion status at the moment, the system effectively logs movement data to support ongoing analysis of worm behavior and environmental responsiveness. This automated tracking enhances monitoring efficiency and contributes to optimizing composting conditions.

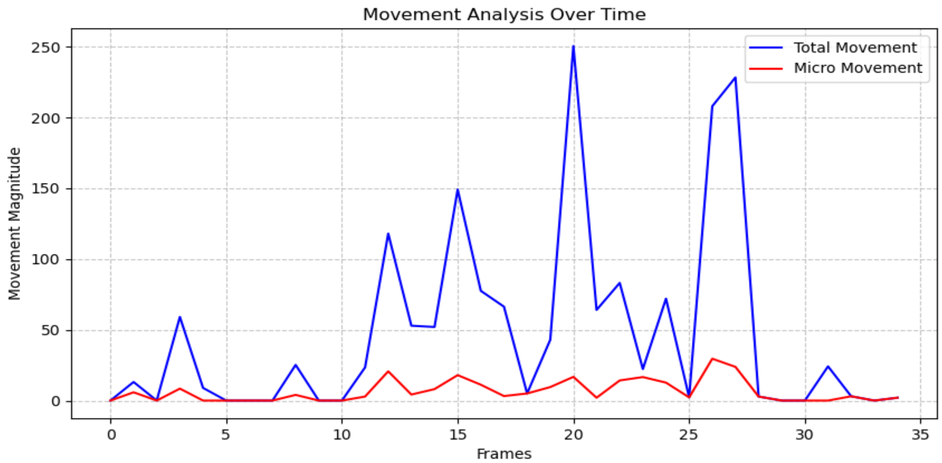


FIGURE 11:VERMICOMPOSTING DATASETS RESULTS

The line graph, titled "Movement Analysis Over Time," tracks movement magnitude across 35 frames. The blue line represents the "Total Movement," which demonstrates considerable volatility throughout the sequence. Noticeable surges in total movement occur around frame 12, frame 16, frame 21, and frame 27, indicating periods of significant activity. In contrast, the red line, representing "Micro Movement," exhibits much smaller fluctuations and generally maintains a lower magnitude compared to the total movement. This suggests that while the overall movement experiences substantial peaks and valleys, the micromovements remain relatively constrained. The graph provides a visual comparison of these two types of movement over the observed timeframe.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

This research successfully designed, developed, and evaluated a low cost, AI based system for monitoring vermicomposting processes using a Raspberry Pi and computer vision techniques. The prototype demonstrated that realtime monitoring of worm health and compost conditions is feasible without relying on expensive sensor arrays. By leveraging lightweight convolutional neural network models and affordable embedded hardware, the system achieved a classification accuracy of over 92% during field testing, confirming its effectiveness in real world scenarios.

The proposed system contributes significantly to sustainable agriculture by offering a scalable and accessible solution for smallholder farmers, particularly in resource constrained regions. Realtime monitoring enables timely interventions, ensuring optimal compost quality and enhancing soil fertility. Furthermore, the integration of cloud based platforms for data visualization and storage extends the utility of the system, enabling remote monitoring and fostering data driven decision making in agricultural practices.

Overall, this research addresses a critical gap in vermicomposting management by providing a practical, affordable, and efficient alternative to traditional manual monitoring methods. The successful implementation of the system highlights the potential of combining embedded systems, AI, and IoT technologies to promote environmental sustainability and agricultural innovation.

6.2 Recommendations

Based on the findings of this research, several recommendations are proposed for enhancing the system and facilitating its broader adoption. First, future implementations should consider incorporating additional environmental sensors, such as temperature, humidity, and gas emission sensors, to provide a more comprehensive analysis of composting conditions. Although the current system focuses on image-based analysis, integrating sensor data could further improve monitoring accuracy and enable predictive analytics [1].

Second, efforts should be made to optimize the convolutional neural network models for greater efficiency. Techniques such as model pruning, quantization, or the use of more lightweight architectures like Mobile Net could reduce processing latency and energy consumption, making the system even more suitable for deployment in off grid environments.

Third, to improve robustness, particularly under variable lighting conditions, advanced image preprocessing techniques such as adaptive histogram equalization or infrared imaging could be investigated. These enhancements would help maintain high classification accuracy even in lowlight or challenging environmental conditions.

Finally, partnerships with local agricultural cooperatives, government agencies, and nongovernmental organizations should be pursued to promote the adoption of the system among smallholder farmers. Training workshops, demonstration projects, and subsidies could help overcome initial barriers to technology adoption and maximize the system's impact on sustainable agricultural practices.

6.3 Future Work

Although the system developed in this research has demonstrated promising results, several areas warrant further investigation. Future work could explore the development of a multiclass classification model capable of identifying specific worm behaviors or compost anomalies beyond general health status. Such granularity could provide deeper insights into the vermicomposting process and allow for even more precise management interventions [2].

Another avenue for future research involves expanding the system's capabilities to accommodate multiple bins simultaneously, creating a networked monitoring solution for larger vermicomposting operations. This would require optimizing data handling, processing pipelines, and communication protocols to ensure scalability without compromising system performance.

Moreover, integrating machine learning models that can predict compost maturity based on temporal image sequences could offer additional value to farmers. Predictive models could enable optimized harvest times for compost, improving efficiency and profitability.

Finally, comprehensive field trials across diverse climatic and operational conditions would be beneficial to validate system performance across different environments. Such trials would help refine the system's design and ensure its adaptability to a wide range of real world scenario

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