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PAPER

IoT- enabled crop waste mulching machine for sustainable farming: perspective of circular economy

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Keywords: IoT-enabled mulching machine, design failure mode and effects analysis of mulching machine, crop waste management (CWM), environmental sustainability, agricultural technology innovation

Abstract

A large amount of crop waste is generated after crop harvesting. A substantial quantity of waste on the farm is burnt to clear the field, contributing to environmental harm and global warming. The study aims to develop a technological solution for crop waste management (CWM) by designing and developing an IoT-enabled crop waste mulching machine. This initiative addresses the environmental and health issues caused by burning crop waste on farms. The research involves designing and developing an IoT-enabled mulching machine that can be attached to the back side of a tractor. The machine consists of power-transmitting elements, supports, and mechanisms to distribute mulching material evenly onto the plant bed. It incorporates advanced IoT load cell sensors, soil moisture sensors, and proximity sensors to optimize the mulching process based on soil moisture content and to prevent machinery blockages. The IoT-enabled mulching machine effectively manages crop waste by utilizing it in mulch, thus preventing the harmful practice of burning waste. This machine ensures a more efficient, safer, and environmentally friendly approach to mulching, offering significant improvements over traditional manual mulching methods. The novelty of this research lies in integrating IoT technologies within mulching machine. The mulching machine uses sensors to automate and optimize the mulching process, representing a significant technological advancement over conventional methods. The study offers practical benefits by reducing labour requirements, minimizing the risk of injuries, and ensuring a more uniform mulch application. This technology facilitates more sustainable farming practices, aligning with global sustainability goals. The study can potentially revolutionize the agricultural equipment manufacturing industry (AEMI) by shifting the focus toward environmental sustainability. It promotes replacing plastic film mulching machines with more eco-friendly crop waste mulching solutions. This technology has the potential to reduce air pollution, carbon emissions, and mitigate climate. It also enhances soil health through better mulching practices.

1. Introduction

Many countries struggle to handle large quantities of agricultural waste effectively. Their year-round farming activities generate large amounts of agricultural by-products, such as crop waste (Bhuvaneshwari *et al* 2019, Kumar and Joshi 2013). Significant crop waste is burnt due to insufficient sustainable management, resulting in high particulate matter emissions and air pollution. The time between crops is typically short; farmers may find it appealing to burn residues on the field to accelerate and ease tillage for the subsequent crop (Singh *et al* 2008, Bhuvaneshwari *et al* 2019). Farmers burn agricultural waste because it is the most affordable and practical method, believing that it increases the fertility of the soil and aids in the management of weeds, insects, and parasites (Goswami *et al* 2020, Setia *et al* 2020). Paddy waste disposal is also a significant issue in CWM (Werther *et al* 2000). However, many countries have restricted open-air burning because it produces significant air quality concerns (Singh *et al* 2020, Lohan 2018). Air pollution endangers human health and safety (Arai *et al* 2015). Burning crop residue also causes nutritional losses that threaten human health and safety (Govaerts et al 2007, Saharawat 2014, Kaushal and Prashar 2021). Farmers should be aware of the harmful effects of burning agricultural waste and educated on practical usage and solid agricultural waste disposal (Raza *et al* 2019). Many government attempts have mainly concentrated on agriculture and energy despite burning agricultural residue impacting various sectors, such as the environment, farming, economics, societal concerns, education, and energy (Awasthi *et al* 2010, Bhuvaneshwari *et al* 2019).

In the farming segment, adopting sustainable CWM methods is a proper solution to save the environment (Raza *et al* 2019). Crop residue burning may be effectively addressed by combining government actions and legislation with the effective implementation of sustainable management techniques (Bhuvaneshwari *et al* 2019). CWM is essential because it preserves nutrients and enhances soil, plant, and atmosphere continuity. Burning crop waste pollutes the environment and significantly damages plant-needed nutrients (Lohan *et al* 2018). Agricultural waste is a vast reservoir of unused residue resources that might pose financial and environmental risks. The circular economy may transform them into energy and biogoods through conversion processes (Gontard *et al* 2018, Xu *et al* 2021). Crop waste is also used for animal feed and other applications like small- and medium-sized businesses for paper, board, panel and packaging materials (Goswami *et al* 2020, Maurya and Bharti 2020). A few practical, sustainable solutions that may help reduce the issue while protecting the soil's nutrients include composting and the generation of biochar (Kapoor *et al* 2020). Several laws and initiatives focused on encouraging sustainable practices, including converting agricultural waste to electricity (Bhuvaneshwari *et al* 2019).

Due to inadequate rainfall, the agriculture sector has been in trouble for the last few years. In the summer, it is a critical challenge for farmers to save crops like fruit farming by properly planning through the irrigation system (Kodzwa *et al* 2020). So, water can be conserved in fruit farming during the summer by mulching crop waste like sugar cane trash, maize stubble, and wheat stubbles. In the rainy season, crop waste decomposes to form organic fertilizer, which improves soil fertility (Kader *et al* 2017). Mulching is a crucial practice for agricultural sustainability, primarily focusing on water conservation, soil moisture regulation, and weed control (Scaringelli *et al* 2016, Prem *et al* 2020). It plays a pivotal role in mitigating the effects of droughts caused by climate change and variability, with a more pronounced impact on crop productivity during seasons characterized by low rainfall and prolonged dry spells (Kodzwa *et al* 2020). Mulching helps conserve soil moisture, regulate soil temperature, and enhance crop yields. Plastic mulches are particularly effective in controlling the soil environment, while organic mulches offer the benefits of affordability and environmental friendliness (Kader *et al* 2017, López-Urrea *et al* 2020). In dryland contexts, mulching mitigates drought effects, minimizes water loss, enriches soil quality, and optimizes crop production (Splawski *et al* 2016, El-Beltagi *et al* 2022). It also enhances herbal plant productivity, thus mitigating the impacts of climate change (Sharma and Bhardwaj 2017, Thakur and Kumar 2021). Additionally, long-term leguminous grass mulching significantly increases macro aggregates and dissolved organic carbon content, especially in micro aggregates (Gu *et al* 2021, Yang *et al* 2022). Hence, mulching is important for mitigating the adverse effects of rapid industrialization and urbanization on agroecological systems (Iqbal *et al* 2020).

The research problem addressed in this paper consists of an innovative application of crop waste mulching in fruit farming, which simultaneously tackles the challenges of crop waste management and the scarcity of water resources. Specifically, the study focuses on the utilization of crop waste materials such as sugar cane trash, maize stubble, and wheat stubble for mulching purposes. This method is instrumental in conserving water during the critical summer season, highlighting a sustainable approach to agriculture. To enhance the efficiency and effectiveness of the mulching process, we introduce the development of a tractor-operated crop waste mulching machine. This machine is designed to mitigate the limitations associated with manual mulching by incorporating IoT technology. A load cell sensor determines the amount of mulching material that should be incorporated, while a soil moisture sensor measures the moisture content of the soil. Depending on the moisture content in the soil, the user can decide the thickness of the mulch layer. Proximity sensors identify the rotary motion of the threshing drum and transfer drums. If any of the drums is blocked due to wet crop waste, it will alarm the operator. All collected data is transmitted to agriculture practitioners via apps and e-mail. So, this research aims to synthesize and design the crop waste mulching machine, which involves conceptualizing and crafting a machine that meets the demands of modern fruit farming. Furthermore, the objective extends to the actual development of this machine, translating design concepts into a functional piece of agricultural technology. A critical part of these objectives is the implementation of IoT within the mulching machine, a step that signifies a move towards smarter, more efficient agricultural practices. This IoT-enabled crop waste mulching machine is the best solution for CWM to protect the environment. Replacing plastic film mulching machines with crop waste mulching machines promotes environmental sustainability in agriculture equipment manufacturing industries.

The research paper follows a structured approach, starting with a literature review, identifying research gaps, and detailing the methodology through a flow chart. Input from experts and practitioners helps to set research objectives. The need for innovation is highlighted due to limitations in manual mulching. The scope and problem are defined, leading to design calculations, Design failure mode and effect analysis (DFMEA), and modeling. IoT integration is crucial for enhancing machine functionality. The mulching machine's construction details and working principles are provided, along with empirical results. The discussion emphasizes the benefits of machine-assisted mulching over manual methods, considering circular economy principles and environmental sustainability. In conclusion, the study underlines the significance of mulching for sustainable agriculture and technological advancement. The research contributes to the existing literature by introducing a crop waste mulching machine integrated with IoT technology, offering a novel agricultural crop waste management solution. Empirical results support its efficacy, while discussions emphasize its benefits over manual methods, contributing to the conversation on sustainable agriculture.

2. Literature survey

A review of some relevant agricultural crop waste management articles from journals identified by a reputed publisher was conducted. The articles were roughly grouped into different domains, such as residue generation, crop waste management challenges, and some solutions to help with crop waste management on a broader basis. The relevance of our research work is highlighted and proved by the survey.

2.1. Agricultural crop waste generation

Goswami *et al* (2020) focused on the generation of agricultural crop waste, especially in the case of rice, and the effect of burning crop residue on soil fertility and the environment. They also discovered several challenges in residue incorporation. Fiksel and Lal (2018) worked on various integrated systems approaches towards waste policies. They also studied the current status of CWM in India. Gontard *et al* (2018) addressed the increase in agricultural residues to fulfill the growing demand of the growing population. However, compared to other waste streams such as rounded wood supply, urban and other garbage, and forest wastes, these residual resources comprised around 50% of the weight of harvested crops and had a potential of 90 million tons of oil Equivalent. Pappu *et al* (2007) discussed the current situation of the country's production and use of harmful and non-hazardous waste.

2.2. Agricultural crop waste management

Maurya and Bharati (2020) discussed the agricultural CRM for sustainable development in the agricultural field. Singh *et al* (2020) investigated the adverse impacts of agricultural residue burning on regional and global air quality, including the healthcare system; additionally, as a result of burning primary crop residues or a high-resolution emulation inventory of air contaminants based on thermal anomalies. Kumar and Singh (2021) found eco-friendly solutions to agricultural residue burning in India's northern and western states. Goswami *et al* (2020) identify that, on average, 0.7% N, 0.23% P, and 1.75% K are present in paddy waste. Consequently, the global production of paddy crop waste with NPK content increases. Ravindra *et al* (2019) developed an integral crop residue management model for sustainable agriculture. They also addressed the effect of open burning of crop waste on air quality and human health. Jethva *et al* (2019) investigated an efficient waste management system for crop residue, which will be needed to eliminate open-field burning of crop residue. Manna *et al* (2018) investigated the potential for organic waste management in agriculture in the country. Additionally, their research is focused on greenhouse gases and crop residue burning. Chivenge *et al* (2007) worked on the varied impacts of long-term tillage and residue management.

2.3. Machines used in agriculture CWM

Ramulu *et al* (2018) emphasized the need for specialized machinery for efficient residue management, highlighting past research on its benefits for soil nutrition and crop yield enhancement. Zhu *et al* (2023) developed a new bilateral counter-throwing soil-covering device to mitigate fire risks in orchards, significantly improving straw mulching efficiency. It ensures uniform soil coverage over straw, optimizes power use, and achieves exceptional performance in field tests, promising advancements in orchard management practices. Jibrin *et al* (2013) emphasized optimizing crop residues to alleviate feed scarcity and introducing technology to crush residues, enhancing livestock nutrition and supporting sustainable agriculture practices. Mady *et al* (2015) explored the efficacy of a chopping machine on agricultural residues, specifically rice straw, aiming to reduce their size and volume. Findings reveal optimal machine productivity, efficiency, minimal energy requirements, and low operating costs at specific operational settings. Additionally, significant outcomes in achieving desired cutting lengths underscore the machine's potential in agricultural waste management, presenting an efficient solution for residue reduction. Ramulu *et al* (2023) introduced a machine designed to efficiently manage crop residue in paddy fields, focusing on chopping and mixing soil. Optimizing operational parameters significantly enhances residue incorporation and reduction. With potential modifications for power efficiency, it promises an effective solution for residue challenges. Parihar *et al* (2022) developed Indo Gangetic Plane's rice-wheat system. Advanced seeders and the Super Straw Management System present solutions for direct wheat sowing into rice stubble, yet adoption lags due to cost and limited awareness among farmers. Hou *et al* (2022) introduced a multifunctional planter that improved soybean replanting after wheat by integrating straw clearing, precision sowing, and mulching. Results show enhanced sowing quality, soil conditions, and soybean yield, significantly boosting economic benefits and sustainability compared to conventional methods. Kumar *et al* (2018) tested tractor-operated rotary mulchers for efficiency in paddy fields, comparing two brands. Findings indicate mulchers effectively manage straw stubble, improving soil health and easing tillage. Differences in capacity, efficiency, fuel consumption, and cutting rate highlight their agricultural benefits.

2.4. Role of IoT in agriculture machines

The integration of IoT technologies in agriculture has unfolded progressively over the years, marking a significant shift towards smarter, more efficient farming practices. Oksanen *et al* (2016) evaluated OPC Unified Architecture's applicability for agricultural machinery telemetry, specifically in a combine harvester's yield monitoring system. They examined both server and client components for remote monitoring in agriculture applications. Dholu and Ghodinde (2018) explored cloud-based IoT applications in agriculture to enhance precision farming by optimizing resource allocation. They discussed developing sensor nodes for monitoring vital agricultural parameters like soil moisture and temperature, enabling automated actuator control for efficient irrigation and climate management.

Similarly, Mat *et al* (2018) highlighted IoT's potential to revolutionize agriculture, which is essential for feeding a growing global population under challenges like climate change. Smart farming, a high-tech approach, uses IoT to improve productivity and sustainability, incorporating modern ICT to optimize operations. Jaiganesh *et al* (2017) also examined IoT's impact on agriculture, highlighting advanced tools like GPS and sensors for data analysis and exchange. They introduced an agriculture cloud, offering farmers management services for crop growth, fertilization, and disease treatment, enhancing productivity while saving time and costs. Waleed *et al* (2020) and Waleed *et al* (2021) developed a smart system employing IoT, GPS, and AI to accurately measure agricultural machinery's work area, addressing the inaccuracies and inefficiencies of manual methods.

Kim *et al* (2020) reviewed IoT applications in agricultural automation within Korea, examining cases, comparing sensor and communication technologies, and discussing limitations and future prospects. They highlighted IoT's role in enhancing agricultural processes through advanced communication technologies like 5G, aiming for increased automation. Rane and Narvel (2021) developed a framework for managing project risks in heavy equipment manufacturing by leveraging IoT technology. Pasi *et al* (2020) also developed a conceptual framework that utilizes IoT technology to improve efficiency and production across supply chain sectors. The framework under consideration emphasizes the exchange of data and the exploitation of resources to enhance the performance of the supply chain. Rane *et al* (2021) proposed use cases for managers employing IoT technologies to facilitate stakeholder engagement. Pasi *et al* (2020) examined the impact of IoT on the assembly line of a smaller-scale transformer manufacturer to increase efficiency, productivity, and safety. Rane and Potdar (2021, 2021) used IoT to improve the agility of Project Procurement Management. Gupta (2021) explored an innovative health monitoring and diagnostic approach for agricultural vehicles, focusing on improving field efficiency and reducing costs. They proposed shifting from traditional, expensive sensor-based systems to more economical, microphone-based mechanisms, leveraging IoT sensor data. Rane and Thakker (2020) explored how IoT could enhance operational flexibility through immediate monitoring and predictive analytics. Farooq and Akram (2021) presented a comprehensive analysis of IoT applications in agriculture; they classified studies by research type and technological solutions, highlighting IoT's role in modernizing agriculture through monitoring, control, and prediction. Xu *et al* (2022) reviewed the impact of agricultural IoT, enhancing output, product quality, and farmer income while reducing labor costs for modernization and intelligence. Rane and Narvel (2022) and Chaudhari *et al* (2022) represented a notable advancement towards ensuring real-time data collection, decentralized resource management, and enhanced security and transparency. This combination promises to foster environmental sustainability and create sustainable ecosystems. Zhang *et al* (2018) and Zhang *et al* (2022) discussed how IoT technologies revolutionize agriculture through Precision Agriculture, focusing on continuous monitoring and precise treatment of soil and plants. They highlighted cloud-based IoT control centres that process real-time data for optimal crop management, enhancing productivity, sustainability, and cost-effectiveness. Finally, Akhter and Sofi (2022) also examined the transformation in agriculture due to IoT and related technologies, making it precise and data-driven. They explored machine learning and data analytics roles in enhancing agricultural productivity and quality.

CWM is a problem that exists all around the world. Farmers burn crop residue for convenience, contributing to air pollution and soil fertility loss. The literature reviewed in this study defines crop residue generation, its impact on the environment, and potential solutions. Mulching is the better solution in crop waste mulching, which conserves water in the summer season and increases soil fertility. In markets, machines are unavailable to mulch crop waste for fruit farming. Here, we replace plastic paper mulching with crop waste mulching, which helps to avoid global warming and soil pollution. However, additional research is needed to design and develop crop waste mulching machines that help agricultural waste management to ensure the agriculture sector's long-term sustainability.

2.5. Research gaps

i. Existing research often focuses on manual mulching techniques. Thus, additional research is essential to cultivate novel designs that maximize the efficacy of mulching, optimize resource utilization, and enhance environmental sustainability.

ii. Despite the increasing importance of sustainable farming and studies on mechanized mulching, more research must be done on enhancing crop waste mulchers. Therefore, it is essential to develop a versatile mulching machine that can effectively meet the changing demands of modern agriculture.

iii. IoT has gathered significant attention and implementation across diverse industries. However, its utilization in agricultural machinery has yet to be thoroughly investigated and explored. Thus, a notable gap exists in the existing research on incorporating IoT to enhance crop waste mulching procedures' effectiveness, accuracy, and sustainability.

3. Methodology

3.1. Research methodology

This research adopts a systematic approach to explore the development of an IoT-enabled crop waste mulching machine to promote the circular economy in sustainable farming practices. The research methodology is divided into the following sections; each section provides an understanding that is valuable to the overall research study.

i. ***Literature survey and research gaps***- A thorough literature survey was conducted to explore existing studies on CWM, mulching techniques, and the use of agricultural machinery. This review highlights significant gaps in current knowledge, particularly in the integration of IoT with mulching processes. Existing literature often highlights the inefficiencies of manual mulching and the need for innovative solutions that leverage technology to enhance productivity and sustainability. This survey laid the groundwork for the proposed research by underscoring the potential benefits of an IoT-enabled approach.

ii. ***Stakeholders inputs and objectives***- Inputs were gathered from stakeholders, including farmers and agricultural practitioners, to define objectives. These insights were crucial in shaping the research objectives, which focus on addressing the limitations of manual mulching methods and exploring the potential advantages of a mechanized solution. The feedback from practitioners highlighted the labour-intensive nature of traditional mulching and the environmental impact of crop waste, emphasizing the necessity for an innovative approach.

iii. ***Scope and problem definition***- The design, development, and evaluation of an IoT-enabled crop waste mulching machine define the scope of this research. The problem statement addresses key challenges in current mulching practices, such as high labour demands, low efficiency, and suboptimal resource use, which hinder the broader adoption of sustainable agricultural practices. By clearly delineating these issues, the research aims to develop a solution that integrates technology to optimize the mulching process.

iv. ***Design and development***- The design phase involved detailed calculations to determine the optimal specifications for the mulching machine, considering factors such as the type of crop waste, field conditions, and operational efficiency. A Design Failure Mode and Effects Analysis (DFMEA) was conducted to identify and mitigate potential failure modes, enhancing the reliability and safety of the machine. Technical drawings were developed to illustrate the machine's components, including the integration of IoT elements such as sensors and connectivity modules.

v. ***IoT implementation***- The integration of IoT is a pivotal aspect of this research, aimed at enhancing the functionality and efficiency of the mulching machine. The system incorporates sensors for real-time monitoring of parameters such as soil moisture, mass of crop waste and machine performance. A microcontroller-based architecture was developed to facilitate data acquisition, processing, and communication with an IoT platform.

vi. ***Construction and operational details***- The construction phase focused on assembling the machine, incorporating both mechanical and electronic components. Detailed operational principles were documented, demonstrating how they address the identified research gaps and fulfill the specified objectives.

vii. ***Results and discussion***- The Results and research findings provide empirical evidence of the machine's performance, facilitating a discussion on its benefits compared to manual mulching methods. The discussion section delves into the broader implications of crop waste mulching, emphasizing its potential impact on circular economy principles and environmental sustainability. By analyzing the benefits of machine-assisted mulching over manual methods, the paper underscores the practical advantages of the proposed innovation.

viii. ***Conclusion***- The study concludes by synthesizing the key findings, reaffirming the significance of crop waste mulching for sustainable agriculture. It highlights that technological advancement is taken into account by the study to overcome existing problem areas in increasing agricultural yields. The IoT-enabled mulching machine not only offers a practical solution to current mulching challenges but also aligns with broader sustainability and circular economy objectives, promoting resource-efficient and environmentally responsible farming practices.

3.2. Experts inputs from farmers/ practitioners

In this study, we gathered inputs from 85 experts, including small, medium, and large-scale farmers, agricultural equipment manufacturers, and agricultural officers, through personal interviews. The experts were selected to represent various stakeholders involved in CWM and sustainable farming practices. Farmers provided valuable feedback on the challenges of the manual mulching process. Agricultural equipment manufacturers contributed insights on the technical feasibility and potential enhancements for machine design, and agricultural officers shared their perspectives on the policy implications and potential impact on sustainable farming practices. The collective inputs from these experts have been instrumental in refining the design and operational aspects of the proposed IoT-enabled mulching machine, ensuring it addresses the practical needs of farmers and aligns with the principles of the circular economy for sustainable agriculture. The expert inputs are as follows.

i. The mulching process should be efficient, minimizing the time required for operation at least 50% less as compared to the manual process, and the machine should be designed to be economically viable for farmers of all scales.

ii. The machine should have adjustable settings to accommodate varying row widths between different crops, ensuring flexibility and adaptability in diverse farming conditions.

iii. The design should focus on automation and ease of use to significantly reduce the dependency on manual labor; manual labor should be reduced by 50%, thereby lowering operational costs and increasing productivity.

iv. Safety features must be integrated into the machine to protect operators during use, including safeguards against mechanical hazards and ergonomic design considerations.

v. The machine should ensure an even and consistent distribution of mulching material across the field, promoting optimal soil coverage and nutrient distribution.

vi. The machine should be designed for durability and ease of maintenance, with minimal downtime and low-cost maintenance needs to enhance its long-term usability.

vii. The machine should be capable of spreading soil over the mulched material, enhancing soil-mulch interaction and preventing wind displacement.

viii. The flow rate of the mulching material should be easily adjustable to match varying crop and field conditions, ensuring precise application and efficient resource use.

3.3. Need of the innovation

In agriculture, a large amount of crop waste is generated after harvesting. Farmers have been burning all this crop waste on the fields, directly contributing to 41%–53% of environmental pollution (Bhuvaneshwari *et al* 2019). It is necessary to consider waste as a potential resource rather than undesirable and unwanted. The agriculture sector is heavily dependent on rainfall, and in the last few years, the agriculture sector has been in trouble due to a lack of rainfall. For water conservation, farmers use this crop waste in the agricultural sector. We can avert environmental pollution by utilizing this crop waste as a by-product for mulching.

3.4. Scope

This machine will fulfil the requirement of fruit farmer and their farm by a uniform distribution of mulching material in a short period compared to manual mulching. Here, we replace plastic paper mulching with crop waste mulching, which helps to mitigate climate change and soil pollution. However, additional research is needed to design and develop crop waste mulching machines that help agricultural CRM to ensure the agriculture sector's long-term sustainability.

3.5. Problem definition

By using crop waste mulching for fruit farming, we solved the issues of crop waste management and scarcity of water. It can conserve water in fruit farming during the summer season. Crop waste like sugar cane trash, maize stubble, and wheat stubble are used in mulching. A tractor-operated IoT enabled crop waste mulching machine can overcome the drawbacks of manual mulching. In this research work, we designed and developed this machine. We also added IOT devices to measure soil moisture and the amount of waste distributed and sense the motion of different moving components.

3.6. Research objectives

The following research objectives are formulated based on identified research gaps and expert inputs.

i. To Synthesize and design a crop waste mulching machine.

ii. To develop a crop waste mulching machine.

iii. To implement IoT in the crop waste mulching machine.

3.7. Novelty

Crop waste mulching machine is an innovative product used in fruit farming for crop waste mulching. The machine is attached to the tractor for mulching fruit farming. This machine takes input power from the tractor's PTO shaft. A spur gear drive is used for power transmission, which transmits the power to each shaft through a belt drive. According to the required speed ratio, the pulley of different diameters is mounted in each shaft. A plumber block bearing helps to support the rotating shaft. The tractor attachment is provided on the frame to connect the tractor. This machine is enabled with IoT technology. A load cell sensor measures the mass of crop waste failing on a calibrated weighing plate. The humidity sensor is used to sense the humidity of the soil. Based on the moisture content in the soil, the user can decide the thickness of the mulch. Proximity sensors identify the rotary motion of the threshing drum and transfer drums. If any of the drums is blocked due to wet crop waste, it will alarm the operator. The present invention collects data like humidity and the amount of material distributed. All this data is transferred to Aurdino with an integrated Wi-Fi module. All collected data is sent to farmers through the app and e-mail. The present invention reduces time and labour costs during crop waste mulching.

4. Design of crop waste mulching machine

The design of the IoT-enabled crop waste mulching machine is central to its functionality and effectiveness in sustainable farming. This section outlines the detailed design process, encompassing the conceptualization, component selection, and detailed design calculations. The machine's design prioritizes operational efficiency, ease of use, and adaptability to various crop waste types, ensuring it meets the diverse needs of modern agricultural practices. Key design elements include robust mechanical components like power transmitting elements, supporting elements, threshing drums etc. A comprehensive Design Failure Mode and Effects Analysis (DFMEA) was conducted to identify potential risks and optimize the machine's reliability and safety. By systematically addressing mechanical aspects, the design process ensures that the mulching machine not only performs effectively but also aligns with sustainability and circular economy principles. The components used in the mechanism of the crop waste mulching machine are shown in table 1.

Table 1. List of components with their material, quantity and function for the mulching machine.

Sr no.	Name of component/part	Material	Quantity	Function
1	Frame	Structural Steel	1	All components are assembled on the frame.
2	Tractor attachment	Structural Steel	1	By using a tractor attachment, the machine can attach to the tractor.
3	Shafts	C55Cr75	8	Shafts are the power-transmitting elements. The threshing drum and transfer drum are mounted on the shafts.
4	Bearings	High carbon chromium steel, 100Cr6	16	Bearing support to all thresher and transfer drum shafts.
5	Pinion	Alloy steel—30Ni4Cr1	1	Pinion and gear pair is used to rotate threshers and transfer rotor in the opposite direction to transfer mulching material.
6	Gear	Alloy steel—30Ni4Cr1	1	
7	Pulleys	CI	8	Different diameter pulleys are mounted on shafts to obtain varying speed ratios.
8	Belts	Synthetic and natural rubber	6	The belt drive transfers the power between various shafts.
9	Threshing Drum	Gray CI	2	Crush the mulching material and transfer it in a downward direction.
10	Transfer Drum	Gray CI	2	Transfer mulching material in the downward direction.
11	Hopper	MS	1	The hopper is the feeder of crop waste/ mulching material.
12	Adjustable Exit ducts	MS	2	Transfer the crop waste/ mulching material onto the crop bed.
13	Keys	C55Cr75	10	To lock relative motion between pulley and shafts.
14	Soil Spreader	Gray CI	2	To push the soil on the crop bed

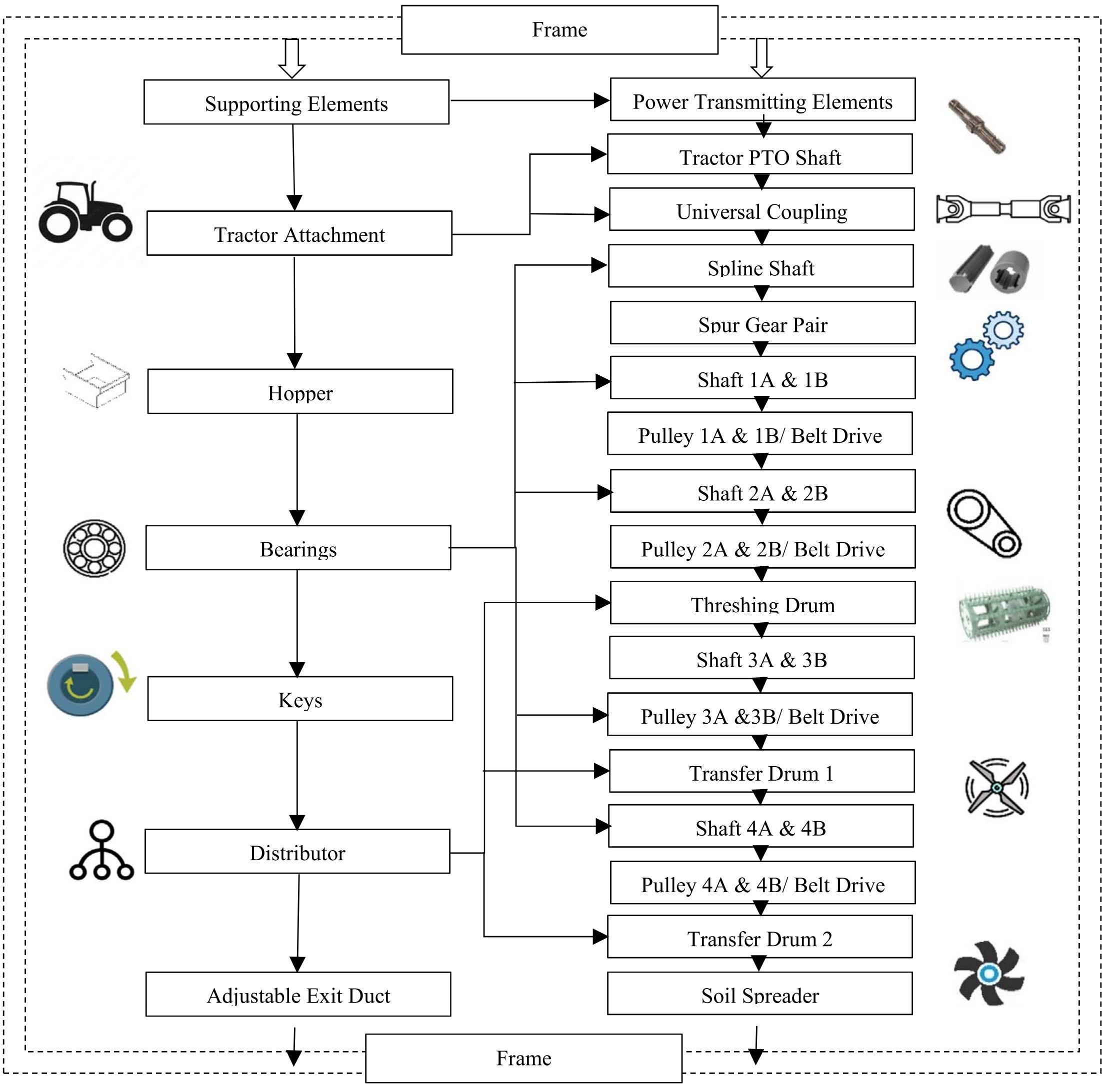


Figure 1. Components used in Crop waste mulching machine (source: Authors' own creation). Note: The detail design calculations and Design Failure Mode and Effects Analysis (DFMEA)are added in appendix.

The sequence of components used in the mechanism of the crop waste mulching machine is shown in figure 1.

5. Drafting of crop waste mulching machine

The drafting of the IoT-enabled crop waste mulching machine involved creating detailed 2D views to provide a comprehensive visualization of its design and structure. The drafted views include the front, top, and side views, each offering critical insights into the machine's component layout and overall configuration. The drafted views include the front, top, and side views, each offering critical insights into the machine's component layout and overall configuration. The part list of the crop waste mulching machine is shown in table 2.

Figure 2 shows a front view of the mulching machine, which illustrates the vertical arrangement of the primary components, including the Tractor, Hopper, Rotor blades, Soil spreader, Duct, and PTO Shaft. This view highlights the structural framework that supports the machine, emphasizing the accessibility and alignment of the key functional parts.

Figure 3 shows a side view that offers a longitudinal section of the mulching machine, detailing the depth and layering of components. This view is particularly useful for visualizing the alignment of the thresher and rotor blades with the drive mechanism, ensuring optimal interaction for efficient mulching. The side view also displays the positioning of the adjustable ducts and distributor. It also shows Connectivity pathways for data transmission between sensors and the microcontroller, illustrating the integration of IoT elements within the mechanical structure.

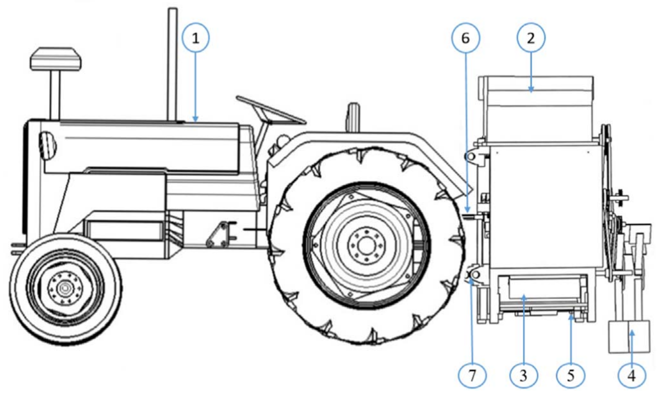


Figure 2. 2D front view of crop waste mulching machine.

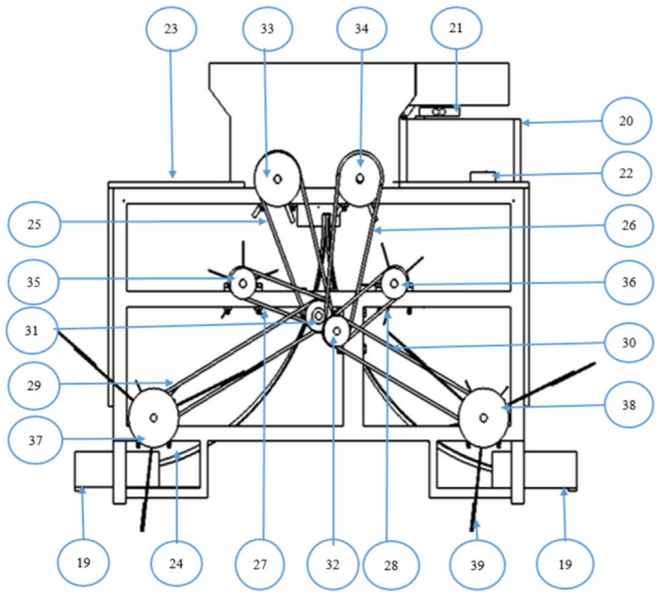


Figure 3. 2D side view of crop waste mulching machine.

Table 2. Part list of mulching machine.

Part no	Part name	Part no	Part name	Part no	Part name
1	Tractor	14	Driven Shaft 4A	27	Belt drive 3A
2	Hopper	15	Driven Shaft 4B	28	Belt drive 3B
3	Rotor blades	16	Thresher	29	Belt drive 4A
4	Soil spreader	17	Gear	30	Belt drive 4B
5	Duct	18	Pinion	31	3 Ply pulley on driving shaft
6	PTO Shaft	19	Adjustable Duct	32	3 ply pulley on driven shaft
7	Tractor attachment	20	Calibrated weighing plate	33	Pulley 2A
8	Gear Shaft	21	Load cell sensor	34	Pulley 2B
9	Pinion shaft	22	Box panel	35	Pulley 3A
10	Driven shaft 2A	23	Outer frame	36	Pulley 3B
11	Driven Shaft 2B	24	Distributer	37	Pulley 4A
12	Driven Shaft 3A	25	Belt drive 2A	38	Pulley 4B
13	Driven Shaft 3B	26	Belt drive 2B	39	Soil Spreader

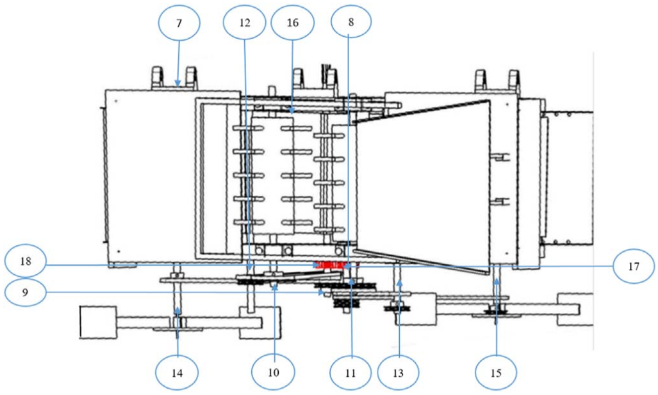


Figure 4. 2D top view of crop waste mulching machine.

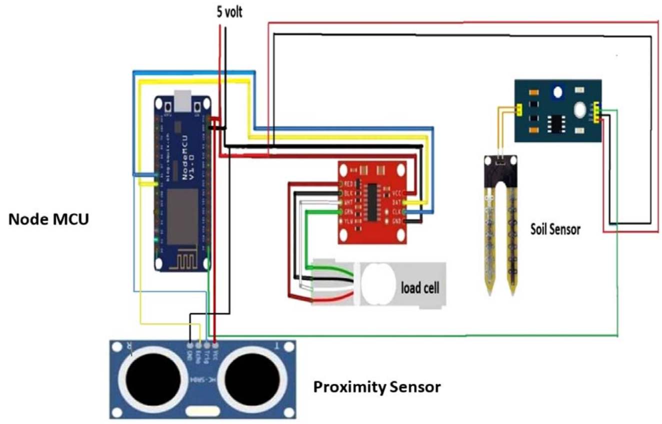


Figure 5. Circuit diagram to implement IoT in mulching machine.

Figure 4 shows the top view and provides a detailed overview of the machine's horizontal layout, showcasing the arrangement of internal components and their spatial relationships. This view is crucial for understanding the flow of crop waste through the machine, from the hopper to the exit duct. The top view also reveals the tractor attachment, soil spreader and power-transmitting elements.

Together, these 2D views provide a complete representation of the mulching machine, facilitating a thorough analysis of its design and functionality. The drafting process ensures that all components are optimally positioned to enhance performance, reliability, and safety. Additionally, these views serve as a foundational reference for further development and potential scaling of the machine.

6. IoT implementation in crop waste mulching machine

The IoT architecture is shown in figure 5. Using the HX711 Load cell amplifier module, we are interfacing a 40 Kg load cell to the Node MCU ESP8266 as part of this IoT innovation. The HX711 is a 24-bit precision analog-to-digital converter (ADC) intended for direct bridge sensor interface in weighing scales and industrial applications. The HX711 load cell amplifier converts strain gauge and load cell data into measurable units. In addition to calibrating the load cell, it is necessary to determine the calibration factor. After the calibration process, we may incorporate that particular factor into our code. As a result, the scale will be exact and accurate. The magnitude of the error increases with the mass by 0.1% to 0.5%. Therefore, we will rectify the inaccuracy present in the weighing scale. The calculated weight will be ultimately presented on the 16×2 I2C LCD Display. Capacitive or resistive soil moisture sensor measures moisture levels in the soil. In this application, the Capacitive Soil Moisture Sensor v1.0 is utilized. By measuring the volumetric water content within the soil, this sensor provides the output of the moisture level. This soil moisture sensor employs capacitive sensing to determine soil moisture levels, compared to the resistive sensing utilized by other available sensors. Place it into the soil and monitor the real-time soil moisture information. This module features an on-board voltage regulator, providing an operating voltage range of 3.3 to 5.5 V. It is ideal for low-voltage microcontrollers that use 3.3 V and 5 V power supplies. Proximity sensors continuously sense the position of moving elements to avoid blockage of the threshing and transfer drum. We will forward the obtained weight and soil moisture values on the Internet of Things platform Blynk Application. As a result, weight and soil moisture may be easily measured by observation from anywhere in the world on the Blynk app dashboard.

6.1. Node MCU

The firmware, rather than the related development kits, is called 'Node MCU.' Open source refers to both the firmware and the prototyping board designs. The programming language used by the firmware is Lua. The firmware for the ES8266 is constructed using the Espersif Non-OS SDK and is based on the eLua project. With the Tensilica Xtensa 32-bit LX106 RIS microcontroller, the ES-12E module containing the ES8266 chip is what makes the Node MCU ES8266 development board. This microprocessor supports a configurable clock frequency of 80 MHz to 160 MHz and supports RTOS. Node MCU features 4 MB of Flash memory and 128 KB of RAM for storing data and programs. It is suitable for Internet of Things projects due to its high computing power, built-in Bluetooth and Wi-Fi, and deep sleep operating features. It is possible to provide Node MCU with a Micro USB cable and a VIN pin (External Supply In). The size of the Node MCU development board is smaller than that of the Arduino UNO. It supports UART, SPI, and I2C interface.

6.2. ESP8266 Wi-Fi module

Controlling the ES-8266 can be done via the local Wi-Fi network or the Internet (after setting up a proxy). The ES-01 module contains GPIO pins that can be programmed via the Internet to turn on an LED or a relay ON/OF. An Arduino/USB-to-TTL converter can program the module through the serial pins (RX, TX).

6.3. Load cell

The silent features of load cell are as follows.

i. **Transducer functionality**: Load cells operate as transducers, converting force into an electrical signal proportional to the force applied. This makes them essential for precise measurement in various applications.

ii. **Varieties and configurations**: There are several types of load cells, such as hydraulic, pneumatic, and strain gauge load cells. The conventional model typically includes four strain gauges configured in a Wheatstone bridge, enhancing accuracy and sensitivity.

iii. **Material and construction**: The described load cell is made from aluminum alloy with an anodized surface treatment, offering durability and resistance to environmental conditions.

iv. **Precision and load capacity**: It has a precision class of C3 and can measure masses up to 40 kg, making it suitable for medium-capacity weighing needs.

v. **Output and calibration**: The load cell has a rated output of 2.0 mV/V with a precision of $\pm 5\%$, which requires amplification through an instrumentation amplifier before use to ensure accuracy.

vi. **Protection and durability**: The load cell is rated IP65, indicating a high level of protection against dust ingress and water jets, which is crucial for maintaining functionality in varied environments.

vii. **Suggested applications**: It is remarkably suggested for use in weighing scales, retail scales, bench scales, and counting scales, underscoring its versatility across different measuring instruments.

viii. **Size and integration**: This load cell's suggested platform size is 350×350 mm, indicating its adaptability to standard weighing platforms.

6.4. HX711 module

The HX711 module combines a load cell amplifier and ADC (Analog-to-Digital Converter) into a small breakout board designed for efficient weight measurement through load cells. By calibrating and connecting this module to a microcontroller, it is feasible to accurately detect changes in the resistance of the load cell, thereby enabling precise weight measurements. This functionality is particularly useful for developing customized industrial scales, managing process controls, or implementing simple detection systems. The module communicates through a dual-wire interface consisting of Clock and Data lines, compatible with the GPIO pins of virtually any microcontroller, simplifying the data acquisition process from the HX711.

6.5. Soil moisture sensor

Soil moisture refers to the quantity or content of water within the soil. This can be determined by utilizing a capacitive or resistive soil moisture sensor. In this system, we used the Capacitive Soil Moisture Sensor v1.0. By quantifying the volumetric water content within the soil, this sensor provides the output of the moisture level. The silent features of Soil Moisture Sensor are as follows.

i. **Operating voltage**: The sensor operates within a voltage range of 3.3 to 5.5 V DC, making it compatible with a wide range of microcontrollers and low-voltage applications.

ii. **Output voltage**: It provides an analog output voltage ranging from 0 to 3.0 V DC, which standard analog input pins of microcontrollers can easily interpret.

iii. **Interface**: The sensor features a 3-pin interface with a PH2.0–3P connector, simplifying integration with existing hardware setups.

iv. **Size**: With dimensions of 99 × 16 mm, the sensor is compact and easy to deploy in various soil conditions, ensuring minimal disturbance to the soil structure during installation.

v. **Analog output**: The sensor delivers an analog voltage output that correlates with the moisture level, enabling continuous monitoring and real-time data acquisition for precise soil moisture management.

vi. **Ease of integration**: The sensor's design facilitates interfacing with various microcontrollers, making it suitable for integration into automated IoT-based agriculture setups and environmental monitoring applications.

vii. These features make the Capacitive Soil Moisture Sensor v1.0 a versatile and effective tool for monitoring soil moisture levels, contributing to optimized irrigation and sustainable agricultural practices.

6.6. Proximity sensor

The proximity sensor uses a contactless detection approach and often uses capacitive or inductive to detect the presence of objects. It continuously monitors the position of moving elements within the mulching machine, such as the threshing and transfer drums, to prevent blockages and ensure smooth operation.

i. **Operating voltage**: The sensor operates at a standard DC voltage range, commonly 6 to 36 V, suitable for integration with agricultural crop waste mulching machines.

ii. **Sensing range**: Typically, it ranges between 1 and 30 mm. This range allows accurate detection of nearby objects to prevent interference with the machine's operation.

iii. **Output type**: Provides a digital output signal (PNP or NPN) that the microcontroller can easily interpret to trigger an appropriate response.

iv. **Response time**: Fast response time of less than 10 milliseconds, enabling real-time monitoring and immediate corrective actions to maintain operational continuity.

v. **Interface**: Equipped with standard 3-wire (brown, blue, black) connections, facilitating integration with the machine's control system.

vi. **Power consumption**: Low power consumption, typically under 200 mA, ensuring minimal impact on the overall power requirements of the machine.

vii. **Protection rating**: A high ingress protection rating, typically IP67 or higher, ensures the sensor is waterproof and dustproof, which is essential for reliable performance in outdoor conditions.

viii. **Real-Time feedback**: Provides continuous, real-time position feedback of mechanical components, enhancing operational efficiency by preventing potential jams and ensuring the smooth flow of materials through the machine.

ix. **Operating temperature**: The sensor is designed to function reliably within a wide temperature range, typically from −25 °C to 70 °C, making it suitable for various climate conditions found in the agricultural sector.

These specifications highlight the proximity sensor's critical role in maintaining the efficiency, reliability, and safety of the IoT-enabled crop waste mulching machine, making it a vital component of the system's overall functionality.

6.7. The significance of IoT technology in mulching machines

The integration of IoT technology in the crop waste mulching machine is a critical component that significantly enhances the machine's performance, usability, and contribution to sustainable farming practices. The significance of IoT technology in mulching machines are as follows:

i. **Real-time monitoring and precision control:** The use of IOT enables continuous monitoring of various parameters like the weight of mulching material and soil moisture; implementing IoT in this system is paramount for the efficient mulching process. By interfacing the HX711 load cell amplifier module with the Node MCU ESP8266, the system accurately measures the weight of crop waste, ensuring precise mulching quantities. This level of accuracy is vital for maintaining consistent mulch application, which is essential for soil health and crop productivity. The use of capacitive soil moisture sensors further allows the machine to adjust its operation based on real-time soil conditions, enhancing resource use efficiency by reducing water consumption.

ii. **Enhanced operational efficiency and automation:** IoT technology enables automation of the mulching process, reducing the need for manual intervention and minimizing human error. The proximity sensors integrated into the system continuously monitor the position of moving components, preventing blockages in the threshing and transfer drums. This predictive capability not only enhances operational efficiency but also prolongs the machine's lifespan by reducing wear and tear due to unpredicted stoppages.

iii. **Data-driven decision-making and remote accessibility**: The IoT system transmits real-time data on weight and soil moisture to the Blynk Application, providing farmers with easy access to critical information from anywhere in the world. This remote accessibility empowers farmers to make data-driven decisions, such as adjusting the mulching process or scheduling maintenance, based on actual field conditions rather than estimates. This capability is particularly valuable in large-scale farming operations where manual monitoring would be impractical or too resource-intensive.

iv. **Contribution to sustainable farming and circular economy:** By utilizing IoT to optimize the mulching process, the machine directly supports sustainable farming practices. The accurate measurement of crop waste and soil moisture allows for the precise application of mulch, reducing the reliance on synthetic fertilizers and improving soil health. This aligns with circular economy principles by promoting the reuse of agricultural residues, enhancing resource efficiency, and reducing environmental impact.

v. **Scalability:** The IoT framework provides a scalable platform that can be easily expanded with additional sensors or upgraded with more advanced data analytics capabilities in the future. This adaptability ensures that the machine can evolve with technological advancements, maintaining its relevance and effectiveness over time.

7. Construction and working of crop waste mulching machine

The present invention relates, in general, to an IOT-enabled green agricultural crop waste mulching machine. The machine is attached to a tractor for mulching fruit farming. In the present invention, the machine operating from tractor PTO is connected to the rear side of the tractor. The rated speed of the tractor varies from 500 rpm to 2700 rpm. According to this speed, the speed of the machine will vary. The flow rate of crop waste depends on the tractor's speed, so it can uniformly spread crop waste on the plant beds. Figure 6 shows exemplary representation and an exploded view of the invention. The machine is connected to the rear side of the tractor through tractor attachment. In this invention, all components are mounted on a frame made by C channel and angles. The pinion shaft is mounted on a frame with the help of a ball bearing and plumber block. The pinion shaft is connected to the tractor PTO through universal coupling and splines to allow misalignment between the PTO and the pinion shaft. The gear shaft is mounted on a frame with the help of two bearings and a plumber block. The pinion shaft and gear shaft are parallel to each other. Pinion and gear are mounted on respective shafts so that they mesh with each other. The pinion and gear rotate in opposite directions.

Driven shaft 2A and driven shaft 2B are mounted parallels on the top side of the frame with the help of bearings. Driven v- pulley 2A is mounted on driven shaft 2A, similarly to Driven v- pulley 2B driven shaft 2B. Power is transmitted from the pinion shaft and gear shaft to shaft 2A and shaft 2B through belt drives 2A and 2B, respectively. Threshing drums with an adjustable lever are mounted on Driven shaft 2A and driven shaft 2B, which rotates in the opposite direction. Driven shaft 3A and driven shaft 3B are mounted in parallel ways on the middle side of the frame with the help of bearings. Driven v- pulley 3A is mounted on driven shaft 3A similarly Driven v- pulley 3B driven shaft 3B 25. Power is transmitted from the pinion shaft and gear shaft to shaft 3A and

Figure 6. Fabricated model of crop waste mulching machine.

shaft 3B through belt drives 3A and 3B, respectively. Rotor blades are mounted on driven shaft 3A and drive shaft 3B, which rotate in opposite directions.

Driven shaft 4A and driven shaft 4B are also mounted in parallel way on the bottom side of the frame with the help of bearings. Driven v- pulley 4A is mounted on driven shaft 4A, similarly to Driven v- pulley 4B driven shaft 4B. Power is transmitted from the pinion shaft and gear shaft to shaft 4A and shaft 4B through belt drive 4A and 4B, respectively. Rotor blades are also mounted on Driven shaft 4A and driven shaft 4B, which rotates in opposite directions. The hopper is mounted on the top side of the frame. A calibrated weighing plate is mounted on the load cell sensor on one side of the hopper. Aurdino microcontroller is fitted in the box panel. The distributor is inserted at the center of the frame. Adjustable ducts are mounted on the outer side of the frame. So, according to the change in distances between two lanes of plants, the duct size will be changed. The soil spreader is mounted on drive shafts 4A and 4 B, which add the required soil to the crop bed.

The rated speed of the tractor varies from 500 rpm to 2700 rpm. According to this speed, the speed of the machine will vary. The power from the PTO of the tractor transfers to the machine driving shaft through the propeller shaft and hook joint. Crop waste will feed into the hopper. A load cell sensor measures the mass of crop waste failing on a calibrated weighing plate. Then, crop waste material will fall on the top thresher drums mounted on driven shafts 2A and 2B, respectively. It will crush the crop waste to the required size and push it downward. The middle and bottom rotor blades, which are mounted on shafts 3A, 3B, 4A and 4B, respectively, force the material towards the exit duct. Belt drives rotate these drums from the driving pulley. The flow rate of crop waste depends on the speed of the tractor. The waste material will uniformly spread through the exit duct on the crop bed.

The humidity sensor is used to sense the humidity of the soil. Based on the moisture content in the soil, the user can decide the thickness of the mulch. After crop residue mulching, the Soil spreader spreads the required amount of soil on a bed of plants. Further, the present invention is effective in fruit farming areas and low rainfall areas. Proximity sensors identify the rotary motion of the threshing drum and transfer drums. If any one of the drums is blocked due to wet crop waste, it will alarm the operator. The present invention collects data like humidity and the amount of material distributed. All this data is transferred to Aurdino with an integrated Wi-Fi module (IoT). All collected data is sent to farmers through the app and e-mail. The present invention reduces time and labour costs during crop waste mulching.

8. Results and discussion

Our research effectively developed an innovative IoT-based crop waste mulching machine and subsequently demonstrated it within the agriculture sector. The experimentation was conducted on a 1-acre fruit farm for 1 month, during which we performed 5 tests under varying operational conditions to evaluate the performance, efficiency, and overall impact of traditional manual mulching methods and the IoT-enabled crop waste mulching machine. This time frame enabled us to observe the performance of the crop waste mulching machine in different environmental and operational conditions. The findings are summarized in table 3, highlighting key parameters such as efficiency, labor requirements, cost implications, scalability, environmental impact, and safety considerations.

The machines exhibited several significant advancements in comparison to conventional manual mulching methods.

Table 3. Comparative results of manual mulching methods and the IoT-enabled crop waste mulching machine on a 1-acre Fruit Farm.

Parameter	Manual mulching methods	IoT-enabled crop waste mulching machine	Percentage difference/ Remark
Efficiency (Coverage Time)	10 h	3 h	70% faster
Labor Required	10 workers	4 workers	60% reduction
Labor Cost (per acre)	Rs. 5000	Rs. 2000	60% reduction
Operating Cost (per acre)	Rs. 5,000 (labor only)	Rs. 2,500 (including fuel)	50% reduction
Initial Investment	None	Rs. 50,000–60,000 (one-time)	Not applicable
Scalability	Up to 1 acre	1 to 100 acres	Highly scalable
Mulch Uniformity	Inconsistent	Consistent (within 5%)	Significant improvement
Soil Moisture Retention	~60% of water capacity	~80% of water capacity	33% increase
Environmental Impact	No emissions	Some emissions (reducible)	Can be mitigated with alternatives prime mover
Maintenance Cost	Negligible	2%–5% of initial cost annually	Additional maintenance required
Safety/ Risk of Injury	Higher injury risk	Lower risk	Enhanced safety
Real-Time Monitoring	Not available	Available (via IoT)	New capability introduced

i. The machine achieved an approximate 70% increase in efficiency compared to manual methods, enabling it to cover more fields for mulching. The mulching material is uniformly distributed on the plant bed. It also conserves the resources for crop waste mulching.

ii. This machine minimized the risk of injuries typically associated with manual mulching and reduced labour requirements by about 60%.

iii. Real-time data collection and transmission enables agricultural practitioners to make informed decisions about mulch thickness and distribution and monitor soil moisture conditions.

iv. The mulching process maintained soil moisture at around 80% of its water-holding capacity, an optimal level for most crops. This represents a significant improvement in water conservation compared to unmulched fields.

The results from our study highlight the benefits of integrating technology into CWM. The crop waste mulching machine reduces the time and labour costs associated with mulching and potentially increases farmers' profitability. The environmental impact of this innovation is particularly notable. By providing an alternative option to burning crop waste, this machine reduces air pollution and greenhouse gas emissions, addressing a significant environmental issues. Furthermore, the IoT functionalities of the equipment signify an advancement in agriculture and its equipment's manufacturing industries. Agricultural practitioners can enhance crop productivity and resource utilization by implementing real-time monitoring. It is critical to modify agricultural practices in response to environmental changes in global warming. This technology feature is particularly important for facilitating such adaptations.

However, the implementation of these machines also has some barriers. The machine's initial investment and the tractor requirement are unaffordable for small farmers. Furthermore, training and technical assistance are required to ensure farmers can utilize and maintain this machine effectively. Finally, our research showcases the capacity of IoT-enabled technologies to crop waste mulching machines. By addressing the issue of crop waste management, the crop waste mulching machine promotes sustainable agricultural practices. Further initiatives should be focused on enhancing this machine's use and supplying the necessary assistance to farmers for implementation.

8.1. Benefits of crop waste mulching by machine over manual mulching

Following table 4 shows the key differences and benefits of crop waste mulching by machine over manual mulching.

8.2. Perspective impact of crop waste mulching on the circular economy (CE)

As mulching with crop residue shows a novel method to accelerate CE in agriculture sector. This method implicitly embraces the principles of reduce, reuse and recycle. It provides another way to solve the long-term sustainability of agroecosystems and continue their contribution to the global economy.

Table 4. Benefits of crop waste mulching by machine over manual mulching.

Sr no.	Features	Manual crop waste mulching	Crop waste mulching by machine
1	Manpower	Manual mulching requires significantly more manpower than mechanized methods. Human labor is needed because every aspect of the mulching process, from spreading to adjusting the mulch, must be handled manually.	Machines can reduce manpower requirements by 70%–90%, depending on the operation's scale and machine efficiency. This reduction is critical in minimizing labor costs and addressing labor shortages in agriculture.
2	Cost	Although manual mulching does not involve initial capital costs, but the ongoing labor costs can be higher. Over time, especially in larger operations, the cumulative cost of labor can surpass the one-time expense of purchasing a machine.	The initial investment for these machines ranges from Rs. 50,000/- to 60,000/-, which is necessary due to the sophisticated technology and machinery size. Although this presents a barrier for small-scale farmers, it leads to a 70% reduction in operating costs, primarily due to the decreased need for manual labor, making it a cost-effective solution in the long run.
3	Efficiency	The process is time-consuming and labor-intensive, which becomes particularly challenging during peak agricultural periods when timely mulching is critical for protecting crops.	The efficiency of machines, which operate up to 70%–80% faster than manual methods, becomes evident almost immediately. This speed is crucial during peak agricultural seasons when timely mulching is essential for soil health and crop productivity.
4	Scalability	Manual mulching is practical and feasible only in smaller areas, typically less than 1 acre. The physical demands and time required to mulch larger areas manually are not economically or practically viable.	This machine has been seen to work impressively in both small and large areas, having the capacity to work as small as 1 acre and as large as 100 acres. Their main advantage is economies of scale, which makes them a great tool for this part of agriculture, where they can constantly work for extended periods.
5	Precision	The manual mulching method is less precise as compared to the mulching machine.	This machine's multifunctionality has benefited farmers who need specific mulch application techniques. Such machines can achieve not only a correct and the same mulch layer but also the optimum soil temperature, humidity, and weed suppression.
6	Accessibility	It is more accessible for small-scale farmers with limited resources.	It requires a significant initial investment, which might be a barrier for small-scale farmers. Financing options and subsidies could improve accessibility.
7	Thickness of Mulch layer	Manual mulching methods are less efficient and produce less results. The variation in mulch depth and layering amounts creates an adverse influence on soil temperature, moisture content, and weed control, which is notorious for determining crop performance.	This machine can keep a mulch level thickness within the 5% range of the required thickness value. Thereby, using automated controls and sensors that change the amount of mulch in response to constant feedback information, farmers get the precision to do it on time.
8	Flexibility	Manual mulching is flexible as compared mulching by machine. Farmers can choose various types of crop waste mulch and apply them in different ways depending on specific crop requirements and soil conditions.	This machine contribute numerous advantages. However crop waste mulching machines may be limited to specific types of mulch and application methods. This limitation affects farmers who use multiple crop waste mulching materials, possibly needing additional solutions or equipment.
9	Environmental Impact	Since manual mulching does not require fuel or energy, it has no carbon footprint. This feature makes it especially attractive in areas and farming methods prioritizing ecological impact reduction and sustainability.	Besides, crop waste mulching machines with tractors are responsible for the emission of greenhouse gases because of the fuel consumption. At the same time, modern technology provides a chance to use biofuel or electricity as power for machines so that they emit a less carbon dioxide.
10	Maintenance	The cost of maintenance is very low because the tools that are needed for manual mulching are basic and they don't involve the use of complicated machines. So it will reduce the equipment cost.	Regular maintenance, which requires 2%–5% of the initial cost, must be ensured to prolong the lifespan and efficiency of the machines. Depending on machine use and operational modes, reprehensible repairs can rise up to 3% in overall extra costs per year.
11	Safety		

Table 4. (Continued.)

Sr no.	Features	Manual crop waste mulching	Crop waste mulching by machine
		There is a risk of human injuries in manual mulching as the material is handled manually.	Adopting mulching machines considerably reduces the risk of physical injury to workers. Automating the mulching process minimizes direct human interaction with machines and mulching material, enhancing safety in agricultural operations.

i. **Augmenting resource efficiency**- Reusing crop waste for mulching is an alternative to inefficient disposal methods such as burning or landfilling, which have significant adverse environmental impacts. This method minimizes the need for external inputs like chemical fertilizers and plastic mulching paper film.

ii. **Agriculture CWM**- Crop waste mulching resolves the challenges of agricultural CWM. Mulching reuses crop waste in the agricultural field instead of burning it. Mulching method reduces air pollution and greenhouse gas emissions from crop waste combustion.

iii. **Environmental footprint reduction**- Crop waste mulching comprises several environmental advantages. The physical presence of organic materials in mulch encourages the stabilization of soil carbon content due to the ongoing decomposition process. This technology, which reduces the carbon dioxide level in the atmosphere, is the key concession for climate change mitigation. Mulch helps save the soil and water, dealing with soil erosion and water shortage to underline its significance to the environment.

iv. **Economic boost** - When crop waste is used in mulching, there could be cost savings and new income opportunities for farmers in agriculture. It reduces water, fertilizers, and pesticide requirements and cuts operational expenses, but the increased yield and crop health stand a chance of pushing higher incomes for farmers. However, another aspect is favourable for the further growth of the same industry, namely the design of equipment and schemes for producing agricultural machinery and processes. New markets are developed, and new jobs are created in eco-friendly agriculture technology.

v. **Enhancement of soil health and productivity** - The CE program compels mulching as a fundamental step; therefore, mulching is always an indispensable part of the CE. Mulching helps build up the soil structure, texture and fertility and nourishes microorganisms, ensuring a healthy and lively soil ecosystem. Better soil quality elicits ecologically friendly agricultural procedures, leading to the longevity of food production and resilience against climate change.

8.3. Perspective impact of crop waste mulching on the environmental sustainability

Crop waste mulching has many environmental consequences, including impacts on biodiversity, water preservation, carbon sequestration, the soil health, and decreasing pollution. Following are the impact of crop waste mulching on environmental sustainability.

i. **Soil and biodiversity:** By recycling crop waste as mulch, soil quality is enhanced, eventually leading to an increased multifaceted aspect of agriculture. Over time, organic mulch's natural decomposing process is maintained, eventually donating nutrients and structural integrity to the soil. These are the factors of natural fertilizers that make the soil more efficient in retaining water, ensuring drought-resistant crops are in effect.

ii. **Water conservation**- Water conservation is crucial in water-scarce locations. Crop waste mulching is crucial to reduce soil surface evaporation. Maintaining moisture reduces irrigation, saving water and preserving this resource. Mulching also prevents soil erosion, which protects environments from nutrient contamination.

iii. **Carbon sequestration**- Addressing climate change is a critical environmental challenge in today's era. Mulching crop waste has a positive impact on soil by improving carbon sequestration. The organic matter in the mulch functions as a carbon sink by absorbing CO_2 from the atmosphere and retaining it in the soil. By implementing this process, greenhouse gas emissions are reduced and the soil's organic carbon content is increased, leading to enhanced quality and productivity.

iv. **Pollution mitigation**- crop waste mulching has proved to be a highly effective method of addressing pollution through various methods. Therefore, by reducing the reliance on chemical fertilizers and toxic chemicals for crops, the fertilizer can be naturally added and weeds suppressed through soil enrichment and weed control, which can consequently remove the introduction of unnatural pollutants in ecosystems. As an alternative, crop residuals may be burned, which gives off CO_2, suspensions, and more air pollution. Air pollution can be effectively subjugated through these organic matter leftovers as mulch; thus, the consequence will be less toxic gases leading to fresh air, which in turn means a healthy environment.

v. **Improving ecosystem services:** While crop waste mulching is conducive to soil health and water conservation, it also decomposes, generating carbon-rich substances to the atmosphere and reducing pollution. These functions are agriculture producing food, climate stabilization, removing pollutants from water, converting them into nutrients. 'Crop waste mulching' is recognized as the solution that both fortifies agricultural and ecological systems.

Sustainable agriculture requires CWM. It improves soil and plant health, ecological balance, resource preservation, and climate change mitigation. Environmental responsibility and agricultural production are combined using sustainable concepts. A sustainable future for agriculture and the planet demands continued research and improvement of this approach. Agricultural waste enriches and structures soil and increasing biodiversity. This reduces evaporation, irrigation, and soil erosion, conserving water and improving water quality. Lowering chemical fertilizers and pesticides reduces pollution and improves environmental sustainability.

9. Conclusion and future scope

This study emphasizes the considerable challenges caused by agricultural waste. Burning crop waste in the traditional way has been shown to result in significant environmental harm, contribute to global warming and create hazards to the health of humans. Our study focused on developing and implementing an innovative CWM solution. We designed and developed the IoT-enabled crop waste mulching machine. This invention represents a substantial advancement over traditional manual mulching methods, which minimize the labour requirement, mulching quality and risks of labour injuries. This machine attaches to the backside of a tractor and efficiently distributes mulching material to the plant bed. Through a combination of mechanical components and IoT components like load cell sensor, soil moisture sensor and proximity sensors, the machine optimizes the mulching process. The IoT system in crop waste mulching machine allow for continuous real-time data transmission to farmers and agricultural practitioners. This system allows practitioners to close monitoring on mulching process. The machine not only streamlines the mulching process but also contributes to the environmental sustainability of agricultural practices.

By replacing plastic film mulching machines with our crop waste mulching machines, we can significantly reduce the ecological footprint of the agriculture equipment manufacturing industry. Additionally, the enhanced soil mineralization and moisture retention from the mulching process directly benefit crop production. This study highlights the potential of technological innovations in solving complex environmental issues in the agriculture sector. The IoT-based crop waste mulching machine addresses CWM issues and promotes sustainable agricultural practices. This innovative mulching machine demonstrates the significance of incorporating technology for sustainable development. It could serve as a model for agricultural sectors worldwide, thereby contributing significantly to the environmental sustainability of agriculture equipment manufacturing industries. The future direction could be the employment of standalone, independent, self-driving models that do not need a tractor and even some tools. The technology would be accessible to small-scale farmers who might not have the tractors they can afford.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Appendix

A1. Design calculations for crop waste mulching machine

A2. Design of spur gear pair

i. Material selection and parameter calculations

We selected 30 Ni 4 Cr 1 alloy steel for gears, as it is used for high strength applications (Oberg *et al* 2004, 27th ed.).

$$S_{ut} = 1150\ \mathrm{N/mm^2}$$
$$BHN = 500$$

Assume, 20° Full Depth involute gear pair
Tractor PTO speed = 980 rpm.
Gear Ratio, G = 1
Speed of pinion, N_p= speed of gear, N_g = 980 rpm

$$\text{Tractor Power},\ P = 15.4\ HP = 15.4 \times 0.7457 = 11.5\ KW$$
$$G = \frac{Z_g}{Z_p} = \frac{N_g}{N_p}$$
$$\text{Number of teeth},\ Z_g = Z_p = 22$$

If both pinion & Gear are of same material then pinion is weaker member.

ii. Design based on beam strength

$\sigma_b = \frac{S_{ut}}{3} = \frac{1150}{3} = 383.33\ \mathrm{N/mm^2}$ (Budynas and Nisbett 2011, 9th ed.)

Lewis form factor, Y

$$Y = 0.484 - \frac{2.87}{Z_p} = 0.484 - \frac{2.87}{22}$$
$$Y = 0.3535$$

Beam Strength, S_b

$$S_b = \sigma_b \times b \times m \times Y$$
$$= 383.33 \times (10 \times m) \times m \times 0.3535$$
$$S_b = 1355.07\ \mathrm{N\ m^2}$$

iii. Design based on wear strength

Wear strength $S_w = d_p \times b \times Q \times k$ (Norton 2011, 9th ed.)

Where, $d_p = m \times Z_p = 22 \times m$ mm

$$b = 10 \times m\ \mathrm{mm}$$

$$\text{Ratio factor},\ Q = \frac{2 \times Z_g}{Z_g + Z_p} = \frac{2 \times 22}{22 + 22} = 1$$
$$k = \text{load stress factor}$$
$$k = 0.16\left(\frac{BHN}{100}\right)^2$$
$$k = 0.16\left(\frac{500}{100}\right)^2$$
$$k = 4$$
$$S_w = 22m \times 10m \times 4 \times 1$$
$$S_w = 880 \times m^2\mathrm{N/mm^2}$$
$$S_w < S_b$$

Gear pair is weaker hence it should be designed for safety against pitting failure

iv. Effective load (Peff)

$P_{eff} = \frac{C_s \times C_m \times P_t}{C_v}$ (Juvinall and Marshek 2012, 5th ed.)

$$C_s = \text{Service factor} = 1.25$$
$$C_m = \text{load distribution factor} = 1.25$$
$$C_v = \text{Velocity factor} = \frac{6}{6 + 0.622 \times m}$$
$$\text{Velocity of pinion},\ V = \frac{\pi d_p N_p}{60 \times 10^3}$$

$$V = \frac{\pi \times 22 \times m \times 980}{60 \times 10^3} = 1.128\ m\ m/s$$

$$\text{Power Transmitted},\ P_t = \frac{P}{V} = \frac{11.5 \times 10^3}{1.28 \times m}$$

Assume, FOS = 2

$$S_w = FOS \times P_{eff}$$

$$880 \times m^2 = 2 \times 1.25 \times 1.25 \times \left(\frac{11.5 \times 10^3}{1.28 \times m}\right) \times \left(\frac{6}{6 + 0.622 \times m}\right)$$

$$\text{module},\ m = 3.68\ mm \approx 4\ mm$$
$$m = 4$$

v. Dimensions of gear pair (Juvinall and Marshek 2012, 5th ed.)

$$d_p = m \times Z_p = 4 \times 22 = 88\ mm$$
$$d_g = m \times Z_g = 4 \times 22 = 88\ mm$$
$$\text{Addendum} = h_a = 1 \times m = 4\ mm$$
$$\text{Dedendum } h_f = 1.5 \times m = 6\ mm$$

$$\text{centre distance (CD)} = \frac{d_p + d_g}{2} = 88\ mm$$

vi. Precise estimation of dynamics loads by Buckingham's equation (Check for design)

$$\text{Dynamic Load},\ P_d = \frac{21V \times [(bXc)] + P_{t_{max}}}{21V + \sqrt{[(bXc)] + P_{t_{max}}}}$$ (Oberg *et al* 2004, 27th ed.)

$$\text{Where, } b = 40\ mm,\ V = 3.73\ m/s$$

$$\text{Deformation factor},\ c = k\ X\ e\left(\frac{E_p\ X\ E_g}{E_p + E_g}\right)$$

$$k = 0.111,\ E = 207 \times 10^3\ N/mm^2$$
$$e = e_p + e_g$$
$$e_p = \text{error in pinion}$$
$$e_g = \text{error in gear}$$
$$e_p = 8 + 0.63(m + 0.25\sqrt{d_p})$$
$$e_g = 8 + 0.63(m + 0.25\sqrt{88})$$
$$e_p = e_g = 11.99\ m$$
$$c = 275.494 \times 10^3$$
$$P_{tmax} = \frac{C_s \times C_m \times P_t}{v}$$

$$P_{t_{max}} = \frac{1.25 \times 1.25 \times (11.5 \times 10^3)}{3.73}$$
$$P_{t_{max}} = 4817.35\ N$$
$$P_d = \frac{21 \times 3.73(40 \times 275.4 \times 10^3 + 4817.35)}{21 \times 3.73 + (\sqrt{40 \times 275.4 \times 10^3 + 4817.35}}$$
$$P_d = 6074.75\ N$$

Safety against pitting failure

$$S_w = 880\ m^2 = 880 \times (4)^2$$
$$S_w = 14.08 \times 10^3 N$$
$$P_{eff} = P_d + P_{tmax} = 10.89 \times 10^3\ N$$
$$S_w > P_{eff}$$

Gear pair is safe against pitting.

vii. Force analysis of gear pair (Budynas and Nisbett 2011, 9th ed.)

$$\text{Tangential force,}\ \ F_t = \frac{P}{V}$$

$$= \frac{11.5 \times 10^3}{4.51} = 2549.88\ \text{N}$$

Radial force, $F_r = F_t\ \tan \varnothing$

$$= 928.08\ \text{N}$$

Resultant force, F

$$F = \sqrt{{F_t}^2 + {F_r}^2}$$
$$F = \sqrt{2549.88^2 + 928.08^2}$$
$$F = 2713.52\ \text{N}$$

A3. Design of shaft

$$\text{Diameter of gear,}\ \ d_p = 88\ \text{mm}$$
$$\text{Diameter of pulley,}\ \ d_g = 125\ \text{mm}$$
$$\text{Power} = 11.5\ \text{KW}$$
$$\text{Speed,}\ \ N = 980\ \text{rpm}$$

Material of shaft—C55 Cr75 (Oberg *et al* 2004, 27th ed.).

$$S_{ut} = 1050\ \text{N/mm}^2$$
$$S_{yt} = 660\ \text{N/mm}^2$$

i. Calculation of allowable shear stress according to the ASME code

$\tau_{all} = 0.75 \times (0.18 \times S_{ut}) = 141.6\ \text{N/mm}^2$ (Budynas and Nisbett 2011, 9th ed.)

$$= 0.75 \times (0.3 \times Syt) = 148.5\ \text{N/mm}^2$$

Select the value whichever is minimum

ii. Torque transmitted by shaft

$$\text{Power,}\ \ P = \frac{2\pi nT}{60 \times 10^3}$$
$$11.5 \times 10^3 = \frac{2\pi \times 980 \times T}{60 \times 10^3}$$
$$T = 112.05 \times 10^3\ \text{N mm}$$

$$T = (P1 - P2)\frac{d_p}{2}\ \text{Where,}\ \ P1\ \&\ P2 = \text{tension on tight}\ \&\ \text{slack side respectively.}$$

$\frac{P1}{P2} = e^{\mu\theta}$ where, $\mu = 0.24,\ \ \theta = \pi$ (Budynas and Nisbett 2011, 9th ed.)

$$P1 = 1.87\ P2$$
$$112.05 \times 10^3 = (1.87P2 - P2)\frac{125}{2}$$
$$P2 = 2060.68\ \text{N}$$
$$P1 = 1.87 \times 2060.68 = 3853.47\ \text{N}$$
$$\text{Total Force,}\ \ P = P1 + P2 = 5914.15\ \text{N}$$

Refer design of gear,

$$\Sigma MB_v = 0$$
$$- RA_v \times 520 + F_r \times 50 + (P1 + P2) \times 110 = 0$$
$$RA_v = 1511.93\ \text{N}$$

$$\Sigma F_v = 0$$
$$RA_v – F_r + RB_v - P = 0$$
$$1511.93 + 2713.52 + RBv - 5914.15 = 0$$

$$RB_v = 1688.7\ N$$

Vertical bending moment at B& C

$$MB_v = -RA_v \times 520$$
$$= 786.203 \times 10^3\ N$$
$$MC_v = -(P1 + P2) \times 60$$
$$MC_v = 354.84 \times 10^3\ N\ mm$$

Now, Calculate for horizontal forces
Taking moment at B

$$RA_h \times 570 - F_t \times 50 + (P1 + P2) \times 110 = 0$$
$$RA_h = -917.65\ N$$
$$\Sigma F_h = 0$$
$$-RA_h - F_t + RB_h = 0$$
$$= -917.65 - 2713.52 + RB_h = 0$$
$$RB_h = 3467.53\ N$$

Horizontal bending moment at B

$$MB_h = 917.65 \times 570$$
$$= 523.06 \times 10^3 N\ mm$$
$$M_b = \sqrt{(786.203X10^3)^2 + (523.06X10^3)^2}$$
$$M_b = 944.30 \times 10^3 N\ mm$$
$$M_c = 354.84 \times 10^3 N\ mm$$
$$M_{max} = 944.30 \times 10^3 N\ mm$$

iii. Equivalent torque

$$T_e = \sqrt{(K_b \times M_{max})^2 + (K_t \times T)^2}$$ (Budynas and Nisbett 2011, 9th ed.)

$$K_b = 1.5,\ K_t = 1.2$$
$$T_e = \sqrt{(1.5 \times 944.30 \times 10^3)^2 + (1.2 \times 112.05 \times 10^3)^2}$$
$$T_e = 1.42 \times 10^6\ N\ mm$$
$$\tau_{max} = \frac{16T_e}{\pi d^3}$$
$$141.75 = \frac{16 \times 1.42 \times 10^6}{\pi d^3}$$

Diameter of shaft, $d = 29.08\ mm \approx 30\ mm$

A4. Design of key

Both shaft & key are of same material

Dia of shaft, $d = 30$ mm
Length of key, $l = 20$ mm
$h = w$ … for square key
Torque, $T = 112.5 \times 103$ N
Direct shear stress in key

$$\tau_a = \frac{2T}{dWl}$$
$$W = 3.5 \approx 4\ mm$$
$$H = w = 4\ mm$$

A5. Belt drive

i. Speed ratio

Cross section of Belt = V

$$\text{Minimum pitch diameter of pulley}$$

$$\text{D1} = 125\ \text{mm}$$
$$\text{D2} = 175\ \text{mm}$$

Speed ratio (Norton 2011, 9th ed.)

$$\frac{\text{N1}}{\text{N2}} = \frac{\text{D2}}{\text{D1}}$$
$$\text{Speed ratio} = 1.4$$
$$\text{N2} = 700\ \text{rpm.}$$

ii. Pitch length of belt

$$L_p = 2C + \frac{\pi}{2}(\text{D1} + \text{D2}) + \frac{(\text{D2} - \text{D1})^2}{4C} \quad \text{(Juvinall and Marshek 2012, 5th ed.)}$$
$$C = 0.55(\text{D1} + \text{D2}) + 11$$
$$C = 0.55(125 + 175) + 11$$
$$C = 176\ \text{mm}$$
$$L_p = 826.79\ \text{mm}$$
$$(L_p = 1008\ \text{mm})$$

iii. Exact center distance calculation

$$\text{Exact C. D} = A + \sqrt{A^2 - B} \quad \text{(Juvinall and Marshek 2012, 5th ed.)}$$
$$\text{Where,}\ A = \frac{Lp}{4} - \pi\left(\frac{\text{D1} + \text{D2}}{8}\right)$$
$$A = \frac{1008}{4} - \pi\left(\frac{125 + 175}{8}\right)$$
$$A = 134.19\ \text{mm}$$
$$B = \left(\frac{D1 - D2}{2}\right)^2$$
$$B = 625\ \text{mm}$$
$$\text{Exact C . D} = 134.19 + \sqrt{(134.19)^2 - 625}$$
$$= 266\ \text{mm}$$

iv. Find angle of contact for smaller pulley

$$\theta_s = 180\text{–}2\sin^{-1}\left(\frac{\text{D2} - \text{D1}}{2C}\right) \text{For open Belt (Juvinall and Marshek 2012, 5th ed.)}$$
$$\theta_s = 169.21$$

v. Belt velocity and power rating

$$\text{Belt Velocity} = \frac{\pi}{2} \times \text{D1} \times \text{N1} = 3.2m/s\ \text{(Norton 2011, 9th ed.)}$$
$$\text{Power Rating of belt in KW} = 0.74\ \text{kw}$$

A6. Selection of bearing

$$\text{Shaft Diameter} = 30\ \text{mm}$$

Deep groove ball bearing (Budynas and Nisbett 2011, 9th ed.)
Bearing no – 6405

$$\text{Diameter of shaft (d)} = 30$$
$$\text{Outside diameter (D)} = 80$$
$$\text{Width (B)} = 21$$

$$\text{Basic static capacity } (C_o) = 2000\text{N}$$
$$\text{Basic dynamic capacity } (C) = 2825\text{N}$$
$$\text{Maximum Speed } = 7100 \text{ rpm}$$

i. Life expectancy calculation (L10)

$$L_{10} = L_{h10} \times 60 \times \frac{N}{10^6} \text{ (Budynas and Nisbett 2011, 9th ed.)}$$
$$= 40000 \times 60 \times \frac{980}{10^6}$$
$$= 2352 \text{ millions rev.}$$

ii. Equivalent dynamic load (PeA)

$$\text{Radial load, } F_{ar} = R_a = 1768.61 \text{ N (Budynas and Nisbett 2011, 9th ed.)}$$
$$P_{eA} = F_{ar} \times K_a \text{ Where, } K_a, \text{ load facor } = 1.5)$$
$$= 1768.61 \times 1.5$$
$$P_{eA} = 2652.91 \text{ N}$$

iii. Basic dynamic load rating (C)

$$L_{10} = \left(\frac{C}{P_eA}\right)^3 \text{ (Budynas and Nisbett 2011, 9th ed.)}$$
$$C = (L_{10})^{1/3} \times P_{eA}$$
$$C = 35.28 \text{ KN}$$

A7. Design of threshing drum

i. Threshing drum volume

The threshing drum volume is needed to calculate the capacity of the threshing drum and its weight. The threshing drum is designed to have a diameter of 254 mm and a length of 304.8 mm.

The drum has 6 threshing blades measuring 2 mm thick, 304.8 mm, and 150 mm wide.

$$\text{The circumference of drum} = \pi \times D$$
$$= \pi \times 254$$

=797.96 mm

Volume of curve (Vc)

Where, L = drum length,

$$\pi \times D = \text{circumference}$$
$$V_c = 304.8 \times 797.96 \times 1$$
$$= 243.218 \times 10^3 \text{ mm}^3$$

Volume of sides (Vs)

$$V_s = \frac{\pi}{4} \times D2 \times t$$
$$= \frac{\pi}{4} \times 254 \times 2$$
$$= 101.341 \times 10^3 \text{ mm}^3$$

Material of threshing drum is MS

$$\text{Volume of Blades} = 2 \times 304.8 \times 150 \times 6$$
$$= 548640 \text{ mm}^3$$

$$\text{Total volume} = (249.218 \times 10^3) + 101.341 + 548640$$
$$= 893.199 \times 10^3 \text{ mm}^3$$

ii. Evaluation of weight of threshing drum

In order to determine the amount of load being exerted by the drum on Shaft, the weight of threshing drum is determined.

$$W = m \times g$$
$$\text{But } m = \rho \times v$$
$$= 7850 \times 8.93199 \times 10^{-4}$$
$$= 7.01 \text{ kg}$$

$$W = m \times g$$
$$= 7.01 \times 9.81$$
$$= 68.78 \text{ N}$$

A8. Design of frame

Material -Structural steel

C − 75 × 40 × 5 × 7 (PSG College of Technology 2019, 4th ed.)

$$\text{Tensile stress} = 300 \text{ N/mm}^2$$
$$\text{Compressive strength} = 960 \text{ N/mm}^2$$
$$\text{Shear strength} = 345 \text{ N/mm}^2$$
$$\text{Mosulus of elasticity} = 135$$

$$I = 100.49 \times 103 \text{ mm}^4$$

Find moment of inertia (I)

Sections 1–1

$$A1 = A2 = 200 \text{ mm}^2$$
$$X1 = X3 = \frac{40}{2} = 20| \text{ mm}$$

Sections 2–2

$$A2 = 65 \times 5 = 325 \text{ mm}^2$$

$$X2 = \frac{5}{2} = 2.5 \text{ mm}$$

$$\overline{X} = \frac{X1 + X2 + X3}{A1 + A2 + A3}$$
$$\overline{X} = \frac{20 + 2.5 + 2.5}{200 + 325 + 200}$$
$$\overline{X} = 12.15 \text{ mm}$$

$$I_x = I_{xx1} + I_{xx2} + I_{xx3}$$
$$I_{xx1} = I_{xx3} = I_{G1} + A_1 h_1{}^2$$
$$= \frac{bd^3}{12} + 200 + 35^2$$

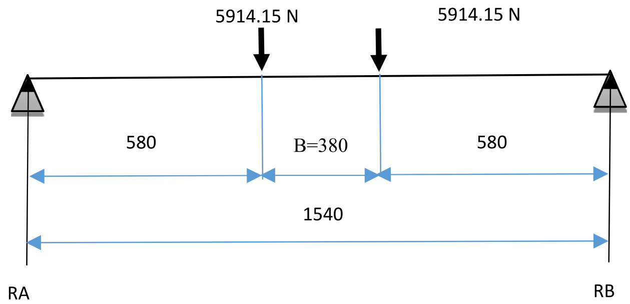
$$= 245.42 \times 10^3 \text{ mm}^4$$
$$I_{xx2} = \frac{bd^3}{12} = \frac{5 \times 65^3}{12}$$
$$= 114.42 \times 10^3 \text{ mm}^4$$

$$I_{xx} = 605.24 \times 10^3 \text{ mm}^4$$
$$I_{yy1} = I_{yy3} = I_{G1} + A_1 h_1{}^2 \ \ldots\ldots\ h_1 = 20 - 12.15 = 7.852$$
$$= \frac{bd^3}{12} + (200 \times 7.852)$$

$$= \frac{5 \times 403^3}{12} + (200 \times 7.852)$$
$$= 38.99 \times 103 \text{ mm}^4$$
$$I_{yy2} = I_{G2} + A_2 h_2{}^2 \ \ldots\ldots h_2 = 12.15 - 2.5 = 9.65$$

$$= \frac{bd^3}{12} + (325 \times 9.652)$$
$$= \frac{65 \times 53^3}{12} + (325 \times 9.652)$$
$$= 30.75 \times 10^3 mm^4$$
$$I_{yy} = 100.49 \times 10^3\ mm^4$$

i. Analysis of frame



By taking reaction

$$RA = P_x = 5914.15\ N$$
$$RB = P_x = 5914.15\ N$$

Bending moment

$$M_x = P_x \text{ for } (0 < x < a)$$
$$M_x = P_a \text{ for } (a < x < a + b)$$
$$M_{max} = P_a$$
$$= 5914.15 \times 580$$
$$= 3.43 \times 10^6\ N\ mm$$

Deflection

$$Y_{max} = \frac{P_a}{24EI} \times (3L^2 - 4a^2) \text{ at, } x = \frac{1}{2} Y_{max}$$
$$= \frac{5914.15 \times 580}{24 \times 135 \times 10^9 \times 100.49 \times 10^3} \times (3 \times 1540^2 - 4 \times 580^2)$$

at, $x = \frac{1}{2}$

$$Y_{max} = -1.41 \times 10^{-5}\ mm$$

A9. Design of hopper

Rectangular hopper

Bottom size $= A \times B$

Top Size $= C \times D$

Vertical $= E$

The area of hopper equates to area sheet 1 × 2 pieces and area of sheet 2 × 2 pieces (Budynas and Nisbett 2011, 9th ed.)

Sheet 1 falling in or sloping by

$$=500 - 300 = \frac{200}{2} = 100\ mm$$

Sheet 2 is falling in or sloping

$$=600 - 400 = \frac{200}{2} = 100\ mm$$

Sheet 1

$$\text{Vertical height} = 400\ mm$$
$$\text{Sloping length} = 100\ mm$$
$$\text{By Pythagoras theorem} = a^2 + b^2 = c^2$$

$$C = \sqrt{400^2 + 100^2}$$
$$C = 412.31 \text{ mm}$$

Sheet 2

$$a^2 + b^2 = c^2$$
$$C = 412.31 \text{ mm}$$

Area of Sheet 1

$$\text{Area of trapezium} = (a + b) \times \frac{h}{2}$$
$$= (0.4 \text{ mt} + 0.6 \text{ mt}) \times \frac{0.4 \text{ mt}}{2}$$
$$= 0.2 \text{ mt}^2$$

We have two sides $=0.2\text{mt}^2 \times 2 = 0.4\text{mt}^2$

Area of Sheet 2

$$\text{Area of trapezium} = (a + b) \times \frac{h}{2}$$
$$= (0.3 \text{ mt} + 0.5 \text{ mt}) \times \frac{0.4 \text{ mt}}{2} = 0.16 \text{ mt}^2$$

We have two sides$=0.16\text{mt}^2 \times 2 = 0.32\text{mt2}$

$$\text{Total area of hopper} = 0.4 \text{ mt}^2 + 0.32 \text{ mt}^2 = 0.72\text{mt}^2$$

A10. Design failure mode and effects analysis (DFMEA)

DFMEA for crop waste mulching machine is essential to identify and address potential failure modes that could affect the machine's performance, safety, and reliability. DFMEA helps ensure that the machine can effectively mulch crop waste without causing harm to the operator or the environment. The following figure A1 shows the steps for a DFMEA of crop waste mulching machine.

i. **Preparation-** The scope and function of all components are defined. All relevant documentation, including design drawings, specifications, and user requirements, are collected from team members from the design, engineering, manufacturing, safety, and service departments.

ii. **Identification of functions-** The function of mulching machines is cutting or shredding crop waste and distributing mulch evenly across the field with minimum power consumption. Secondary Functions also include safety features, ease of maintenance, and other user-friendly features.

iii. **Failure modes-** Potential failure modes are identified for each part of the machine.

iv. **Effects analysis-** Potential effects of each failure mode on the machine, operator, and environment are evaluated. Severity (S) ratings for each effect are assigned by considering the impact on safety, environmental compliance, and machine performance.

v. **Cause analysis-** Failure modes of any phenomenon are thoroughly investigated. Among the significant reasons are material fatigue, poor use, inadequate maintenance or design issues. An occurrence (O) rating is awarded, indicating each reason's probability.

vi. **Detection-** Failure mode are detected by considering preventive actions and design features. Based on their effectiveness, a detection (D) rating is allocated.

vii. **Risk priority number (RPN) -** The RPN for each failure mode is calculated by multiplying the severity (S), occurrence (O), and detection (D) ratings. It can help prioritize the failure modes that require the most urgent attention.

viii. **Mitigation actions-** Actions are prepared to mitigate the highest priority risks. This could involve design modification, implementing new safety features, and providing training and maintenance guidelines to users.

ix. **Re-evaluation-** After implementing mitigation actions, failure modes can be re-accessed to determine the actions' effectiveness. RPN can be recalculated to ensure a reduction of risk.

x. **Documentation and review-** The re-evaluation results, the detected failure modes, their RPNs, the mitigation measures implemented, and the DFMEA process itself should be documented.

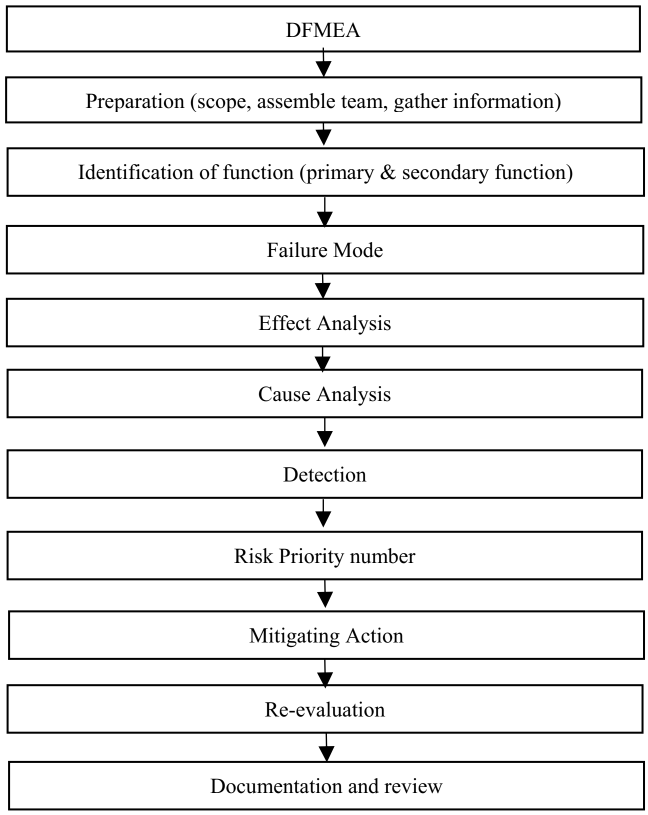


Figure A1. DFMEA steps.

It is one of the proactive activities to identify and address the failure modes by DFMEA so that waste mulching machine can have the best efficiency, safety, and durability. That is why mulching machines should be designed to fit the strict requirements. Through that comprehensive evaluation of the machines and reducing the hazards, we can make them more productive and sustainable in producing outputs.

The DFMEA sheet for the crop waste mulching machine is shown in table A1. DFMEA sheet displays potential failures of different parts, causes, effects, and recommended actions to mitigate these challenges.

i. **Supporting frame**: Due to overload and fatigue, the supporting frame may fail structurally, potentially causing machine collapse and worker injuries. The recommended action is to use more robust materials and avoid overloading.

ii. **Spur gear pair**: A tooth may wear or fail, leading to power loss and machine breakdown, often due to overload or poor lubrication. Recommendations include avoiding misalignment of moving parts and ensuring proper lubrication.

iii. **Shafts**: There is a risk to bending or breaking, stopping the machine by blocking power transmission, mainly due to overloading or improper design. Using higher-grade materials and controlling the flow of mulching material are suggested.

iv. **Bearings**: Bearings can wear, leading to increased friction and overheating. Regular maintenance, such as lubrication and the use of sealed bearings, can prevent this.

v. **Keys**: Key shearing can cause power failure and affect the machine's working. This is generally due to incorrect sizing or material failure. The recommended actions are correct sizing and the use of high-strength materials.

vi. **Belts**: Risks include slipping and failure, affecting power transmission, and increasing pulley wear. Regular inspections and maintaining proper tension are advised.

vii. **Pulleys**: Misalignment and wear can lead to belt wear and loss of power transmission. Proper installation and regular inspections are recommended.

Table A1. DFMEA sheet for crop waste mulching machine.

Sr No	Components	Type of Failure Mode	Potential Effects of Failure	Potential Causes	S	O	D	RPN	Recommended Actions
1	Supporting Frame	Structural failure	Machine instability or damage, create potential injury	Overload, fatigue, improper material	9	3	3	81	Use stronger materials and avoid overloading
2	Spur Gear Pair	Tooth wear/failure	Loss of power, machine downtime	Overload, poor lubrication	7	4	4	112	Avoid misalignment, ensure proper lubrication
3	Shafts	Bending, breaking	Loss of power transmission, machine stops working	Overloading, blockage of threshing drum, improper design	8	3	4	96	Use higher-grade materials and control the flow of mulching material.
4	Bearings	Seizure, wear	Increased friction, overheating, component failure	Poor lubrication, contamination	6	5	3	90	Regular maintenance, use sealed bearings
5	Keys	Shearing	Power failure, misalignment	Incorrect sizing, material failure					
overloading	7	4	5	140	Correct sizing, use high-strength materials				
6	Belts	Slipping, failure	Inefficient power transmission, increased wear on pulleys	Over tension, wear, improper alignment	6	5	4	120	Regular inspection, proper tight side and slack side tension
7	Pulleys	Misalignment, wear	Belt wear, vibration, loss of power transmission	Improper installation, wear	5	4	4	80	Ensure proper alignment, regular inspection
8	Threshing and transfer Drums	Clogging, damage	Failure	Overloading and Clogging due to wet crop waste	9	5	4	180	Implementation of protective measures, regular inspection, Cleaning
9	Hopper	Overloading, blockage	Decrease input efficiency, potential for backflow	Excessive load, poor design	7	3	3	63	Proper continuous input flow, Cleaning

Table A2. Revised SOD and RPN after recommended actions for crop waste mulching machine.

Sr No	Component	Previous S	Previous O	Previous D	Previous RPN	Revised S	Revised O	Revised D	Revised RPN
1	Supporting Frame	9	3	3	81	8	2	2	32
2	Spur Gear Pair	7	4	4	112	5	3	3	45
3	Shafts	8	3	4	96	7	2	2	28
4	Bearings	6	5	3	90	5	3	2	30
5	Keys	7	4	5	140	6	3	4	72
6	Belts	6	5	4	120	5	4	3	60
7	Pulleys	5	4	4	80	4	3	3	24
8	Threshing and Transfer Drums	9	5	4	180	7	4	3	84
9	Hopper	7	3	3	63	6	2	2	24

viii. **Threshing and transfer drums**: These can get clogged or damaged, mainly due to overloading or clogging with wet crop waste. Protective measures and regular cleaning are suggested.

ix. **Hopper**: Susceptible to overloading and blockage, decreasing input efficiency. Ensuring a proper continuous input flow and regular cleaning are recommended.

After implementing mitigation actions, failure modes were re-accessed to determine the actions' effectiveness. RPN were recalculated to ensure a reduction of risk. Table A2 shows Revised SOD and RPN after recommended actions for crop waste mulching machine.

After implementing the recommended actions, the following changes are observed.

i. **Supporting frame**: The performance improved significantly with reductions in all metrics, leading to a new RPN of 32 from an initial 81, highlighting better material use and load management.

ii. **Spur gear pair**: There was a notable improvement in all areas, with RPN dropping to 45 from 112 due to better alignment and lubrication practices.

iii. **Shafts**: Reductions in severity, occurrence, and detectability scores have brought the RPN down from 96 to 28, reflecting the adoption of higher-grade materials and better design.

iv. **Bearings**: Regular maintenance and the use of sealed bearings enhance bearing life, lowering the RPN to 30 from 90.

v. **Keys**: Material strength and sizing adjustments have reduced the RPN to 72 from 140.

vi. **Belts**: Maintaining proper tension and regular inspections have decreased the RPN to 60 from 120.

vii. **Pulleys**: Better installation and regular checks brought the RPN down to 24 from 80.

viii. **Threshing and transfer drums**: The RPN was reduced to 84 from 180 after implementing protective measures and regular cleaning.

ix. **Hopper**: Ensuring continuous and proper input flow along with regular cleaning reduced the RPN to 24 from 63.

Conflicts of interest statement

The authors declare that there is no conflict of interest.

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