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Development of a PLC-Controlled Automatic Punching Machine for Agricultural Plastic Mulch

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ABSTRACT

The use of plastic mulch in modern agriculture requires an efficient and consistent hole-punching process. This study aims to design, construct, and test the performance of an automatic plastic mulch punching machine. The machine is controlled by a Programmable Logic Controller (PLC) and uses a heating system (cartridge heater) for the punching process. The machine frame is made from aluminum profile, and it features three different punching blade diameters (6 cm, 8 cm, and 10 cm). The research methodology included design, manufacturing, assembly, and testing. Test results showed that the machine operated well, achieving a cutting efficiency of 83%. The optimal operating temperature for a good punch quality ranged from 218°C to 234°C, with the best performance observed using the 8 cm diameter blade. This machine successfully improved hole consistency and reduced reliance on manual labor, demonstrating its potential to enhance productivity in agricultural land preparation

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INTRODUCTION

The global agricultural sector continuously seeks innovative methods to enhance productivity, optimize resource use, and improve sustainability. Among the various technologies adopted, plastic mulch films have become a cornerstone of modern horticulture, particularly for high-value crops such as tomatoes, chilies, and melons (Lamont, 1993). These films, typically made from polyethylene or polypropylene, offer significant agronomic benefits, including effective weed suppression, conservation of soil moisture by reducing evaporation, regulation of soil temperature, and prevention of soil erosion and nutrient leaching (Lalitha et al., 2010; Abouziena et al., 2008). By creating a more favorable microclimate, plastic mulch directly contributes to accelerated plant growth, earlier harvests, and increased overall crop yields (Gunawan et al., 2021). These findings are consistent with previous observations on temperature and light regulation under mulched soil conditions, which stimulate vegetative and reproductive development.

Despite these advantages, the preparation of mulched beds presents a significant operational challenge: the perforation of planting holes. Conventional methods rely entirely on manual labor, where workers punch holes into the plastic mulch at regular intervals using simple tools or by hand. This practice is not only time-consuming and physically demanding but also prone to inconsistency. Similar issues were documented by Harahap et al. (2020), who found that manual punching of plastic mulch frequently produces inconsistent hole geometry and spacing. Such irregularities can result in suboptimal plant arrangement, inefficient land utilization, and difficulties during mechanized transplanting. Furthermore, the repetitive nature of this task makes it a bottleneck during critical planting seasons, increasing labor costs and limiting the area a farming operation can prepare in a given time.

Recognizing these limitations, there have been efforts to mechanize the mulch punching process. Previous studies and local innovations have introduced simple manual or semi-automatic punching devices (Harahap et al., 2020; Nabawi et al., 2019). However, these tools often lack precision, require significant human effort to operate, and do not offer a seamless integration of the punching and mulch advancement processes. Many existing solutions are not truly automated, still depending on the operator to position the mulch for each hole, which limits the gains in speed and consistency. The integration of advanced control systems and non-contact thermal punching mechanisms in this specific agricultural application remains underexplored in the existing literature.

To address this gap, this research proposes the design and development of a fully automatic plastic mulch punching machine. The core innovation of this machine lies in the integration of a Programmable Logic Controller (PLC) for precise operational control and a thermal punching system using cartridge heaters. The PLC allows for accurate control over the hole spacing (via a servo motor for mulch feed) and the punching cycle, ensuring high consistency and repeatability. The thermal punching mechanism, where a heated blade melts through the plastic, offers clean and efficient cutting action compared to purely mechanical shearing, which can tear or deform the mulch.

The primary objectives of this study are: to design and construct a fully automatic plastic mulch punching machine utilizing a PLC-based control system and a thermal punching mechanism, to test the performance of the machine by evaluating the quality of the punched holes across different operational parameters, specifically varying punch blade diameters (6, 8, and 10 cm) and heater temperatures and to analyze the machine's operational efficiency and assess its potential to improve upon traditional manual methods in terms of speed, consistency, and labor requirement.

The successful implementation of this machine is expected to provide a viable technological solution for small and medium-scale farmers, reducing drudgery, lowering labor costs, and enhancing the uniformity of crop establishments in mulched cultivation systems.

LITERATURE REVIEW

Plastic Mulch in Modern Agriculture

Plastic mulch, typically made from polyethylene or polypropylene, has become an essential component in modern horticulture. Its primary functions include soil moisture conservation, weed suppression, soil temperature regulation, and reduction of soil erosion and nutrient leaching (Lalitha et al., 2010; Abouziena et al., 2008). By creating a more favorable microclimate, it significantly enhances crop growth, yield, and quality (Gunawan et al., 2021). The most common type used is black-silver plastic mulch, where the black layer inhibits weed growth, and the silver surface reflects light, repelling pests and increasing light availability to plants (Fahrurrozi et al., 2006; Aditya et al., 2013).

The Requirement for Mechanization in Mulch Perforation

Despite its benefits, the process of creating holes in plastic mulch remains a significant bottleneck. The conventional manual method is highly labor-intensive, time-consuming, and often results in inconsistent hole spacing and size (Harahap et al., 2020). This inconsistency can lead to suboptimal plant density, inefficient use of space, and difficulties in subsequent farming operations. Therefore, mechanization is crucial to improve efficiency, reduce labor costs, and enhance the uniformity of cultivation (Nabawi et al., 2019).

Existing Mechanisms for Mulch Perforation

Previous research and development efforts have explored various punching mechanisms:

Manual and Semi-Automatic Tools

Early innovations, such as those by Harahap et al. (2020) and Nabawi et al. (2019), focused on simple hand-held punchers or lever-operated devices. While these tools improved ergonomics over purely manual methods, they still required significant human effort and did not achieve full automation or high-speed operation.

Mechanical Punching

This method uses a sharp blade to shear the plastic. The design of the blade and the roller mechanism is critical, as highlighted by Risantoro (2012), who emphasized the importance of roller material and construction for effective mulch handling. A limitation of pure mechanical punching is the potential for tearing or incomplete cuts, especially if the blades dull over time.

Thermal Punching

This method utilizes heat to melt through the plastic, resulting in a clean and sealed edge. Cartridge heaters are commonly employed for this purpose due to their high-power density, cylindrical form factor, and precise temperature control capabilities (Mukhlis et al., 2010; Noufal et al., 2017). The application of thermal energy for mulch perforation is a promising area that can potentially yield superior hole quality compared to mechanical means.

Control Systems in Agricultural Automation

The advancement towards fully automated equipment is driven by the integration of sophisticated control systems.

Programmable Logic Controllers (PLCs)

PLCs are the backbone of industrial automation due to their reliability, robustness, and ability to handle complex sequential control in harsh environments (D.-1. Kim et al., 1994). In agriculture, PLCs are increasingly used to automate processes such as sorting, packaging, and precise material handling (Y. Sang et al., 2015). Their application in a mulch punching machine allows for precise control over the punch cycle and the synchronization of the mulch feed system.

Servo Motors for Precision Motion

Servo motors, both AC and DC, provide highly accurate control over position, speed, and torque. They are ideal for applications requiring precise linear or rotary motion, such as indexing the plastic mulch to a specific position for each punch (Solomon, 2004). The feedback mechanism in servo motors ensures the system achieves the desired position accurately, which is crucial for consistent hole spacing.

Ergonomics in Machine Design

The design of agricultural machinery must consider ergonomic principles to ensure user safety, comfort, and efficiency. Ergonomics, defined as the science of designing the job to fit the worker, aims to optimize human well-being and overall system performance (Nurmianto, 2003). In the context of this machine, ergonomic considerations include the placement of control interfaces (HMI), the use of emergency stops, and the overall layout to minimize operator fatigue and prevent work-related musculoskeletal disorders (Nurfajriah & Zulaihah, 2010).

Theoretical Framework for Performance Analysis

The performance of the punching machine can be analyzed using established engineering principles:

Motor and Power Calculations

The relationship between torque (τ), force (F), and radius (r) is fundamental ($\tau = F \times r$). The power output of the motor can be derived from its torque and angular velocity ($P_{out} = \tau \times \omega$), while the electrical power input is calculated from voltage and current ($P_{in} = V \times I$). The efficiency (η) is then the ratio of output to input power ($\eta = P_{out} / P_{in} \times 100\%$) (Ghazali et al., 2021; F. Suryatmo, 1986).

Thermal Punching Analysis

The energy (Q) required to heat and melt the plastic can be estimated using the formula $Q = M \times C \times \Delta T$, where M is mass, C is the specific heat capacity of the plastic, and ΔT is the temperature change (Raghavan, 2006). The time required for punching is related to this energy and the power of the heater ($t = Q / P$) (Thermal Analysis of a Heating Element..., 2015).

Cutting Efficiency

The efficiency of the punching process itself can be evaluated by comparing the actual cutting rate (R_output) to the theoretical cutting rate (R_input), expressed as $E = (R_{output} / R_{input}) \times 100\%$ (Analysis of Cutting Efficiency..., ScienceDirect).

Identified Research Gap

A comprehensive review of the literature reveals a clear gap. While individual components like mechanical rollers (Risantoro, 2012), simple automation, and heater applications (Mukhlis et al., 2010) have been studied, there is a lack of integrated research that combines:

1. A fully automated, PLC-controlled system for synchronized mulch feeding and punching.
2. A thermal punching mechanism optimized for different mulch punch diameters.
3. A systematic performance and efficiency analysis of such an integrated system.

This research aims to bridge this gap by designing, constructing, and testing a machine that embodies this integration, contributing a novel solution to the challenge of agricultural mulch preparation.

METHODOLOGY

Research Design and Development Framework

This study employed an experimental research design following the engineering development cycle: design, fabrication, assembly, and performance testing. The research was conducted at the Mechanical Engineering Workshop of Politeknik Negeri Padang from February to August 2025.

Machine Design Specifications and Components Selection

Mechanical System Design:

1. Frame Structure: The main frame was constructed using 40×80 mm and 40×40 mm aluminum profiles, selected for their lightweight properties, corrosion resistance, and ease of assembly. The overall dimensions were 42 cm (length) × 45 cm (width) × 50 cm (height).
2. Punching Mechanism: Three circular punch blades with diameters of 6 cm, 8 cm, and 10 cm were fabricated from stainless steel. The blades were designed to be heated by cartridge heaters (12 mm diameter × 90 mm length, 220V, 300W) for thermal punching.
3. Mulch Feeding System: The system incorporated three main rollers:
   1) Initial mulch roller (diameter: 9 cm)
   2) Punching roller
   3) Take-up roller (diameter: 9 cm)

Rollers were constructed from iron shafts with PVC pipes attached at both ends to enhance grip and accommodate standard mulch roll sizes.

Control and Automation System:

1. Control Unit: A Programmable Logic Controller (PLC) served as the main control unit for coordinating all automated operations.
2. Actuation System: A Mitsubishi HG-KR43 AC Servo Motor (400W, 3AC 108V, 2.4 Nm nominal torque) was employed for precise mulch feeding. The motor was equipped with a high-resolution encoder for accurate position feedback.
3. Temperature Control: An Autonics PID temperature controller coupled with a K-type thermocouple maintained the heater temperature within ±2°C of the setpoint.
4. Safety Features: The system included emergency stop buttons, overload protection, and pneumatic cylinder position sensors.

Machine Assembly Process

The assembly process followed a systematic approach:

1. Primary frame construction using aluminum profiles and screw fasteners
2. Installation of servo motor and roller system with precise alignment
3. Mounting of the punching unit comprising pneumatic cylinder, heater assembly, and punch blades
4. Electrical integration including PLC, HMI, power supply, and safety components
5. Pneumatic system installation for cylinder actuation
6. Final wiring and comprehensive system checking

Experimental Setup and Testing Protocol

Testing Parameters

1. Independent Variables
   1) Punch blade diameter (6 cm, 8 cm, 10 cm)
   2) Heater temperature (range: 190°C to 265°C)
2. Dependent Variables
   1) Hole quality (visual inspection)
   2) Punching cycle time
   3) Energy consumption

Testing Procedure:

1. Preparation

Plastic mulch (black-silver polyethylene, thickness 0.3 mm) was mounted on the initial roller and threaded through the feeding system.

2. Calibration

The HMI was programmed with specific hole spacing parameters (25 cm interval).

3. Operation

The automated punching process was initiated via the control panel, with the PLC coordinating:

1) Servo motor activation for precise mulch advancement
2) Pneumatic cylinder extension for blade contact
3) Heater activation and temperature maintenance
4) Cylinder retraction after punching completion

4. Data Collection

Each test run consisted of 50 punching cycles, with temperature readings recorded every cycle.

Performance Evaluation Metrics

Hole Quality Assessment:

Holes were evaluated based on three categories:

1. Good: Complete, clean-edged holes without plastic residue
2. Fair: Partially complete holes with minor tearing or residue
3. Poor: Incomplete holes or significant plastic deformation

Efficiency Calculations

1. Theoretical Cutting Rate (R_input): Calculated using the formula:

$$R_{input} = A_p \times n$$

where Ap is the cutting area and nn is the rotational speed.

2. Actual Cutting Rate (R_output): Determined from measured punching time and hole quality.
3. Cutting Efficiency (E)

$$E = \frac{R_{output}}{R_{input}} \times 100\%$$

Motor Performance Analysis

1. Angular velocity

$$\omega = \frac{2\,\pi\,n}{60}$$

2. Linear velocity

$$v = \omega \times r$$

3. Output power

$$\tau = F \times r$$

4. Input power

$$P_{in} = V \times I$$

5. Motor efficiency

$$\eta = \frac{P_{out}}{P_{in}} \times 100\ \%$$

Data Analysis Methods

Experimental data were analyzed using descriptive statistics to determine:

1. Optimal temperature ranges for each blade diameter
2. Relationship between operational parameters and hole quality
3. System efficiency under varying conditions
4. Comparative performance of different blade configurations

All tests were conducted in controlled environmental conditions with consistent material properties to ensure data reliability and reproducibility.

RESULTS AND DISCUSSION

Overall Machine Performance and Operational Reliability

The automated plastic mulch punching machine was successfully constructed and demonstrated consistent operational performance throughout the testing period. The PLC-based control system effectively synchronized all operational sequences, including mulch feeding via the servo motor, pneumatic cylinder actuation for the punching mechanism, and temperature maintenance of the heating elements. The machine completed all 250 test cycles (5 experiments × 50 punches each) without system failure, demonstrating robust mechanical construction and control system reliability.

The Human Machine Interface (HMI) proved instrumental in operational efficiency, allowing precise adjustment of punching spacing from 10cm to 50cm with minimal programming effort. The emergency stops system and safety sensors functioned correctly during all operational tests, immediately halting machine operation when activated.

Analysis of Temperature Parameters on Punching Quality

Temperature Optimization for Different Blade Diameters:

The relationship between operating temperature and punching quality revealed distinct optimal ranges for each blade diameter (Figure 1). The 6cm diameter blade achieved optimal performance between 213-220°C, producing clean, complete holes with minimal plastic residue. Below 210°C, the blade failed to adequately melt through the plastic, resulting in incomplete punches that remained attached to the main mulch sheet. Temperatures exceeding 225°C caused excessive melting, leading to irregular hole edges and occasional plastic shrinkage.

The 8cm diameter blade demonstrated the widest effective temperature range (194-234°C), indicating greater operational flexibility. This blade size maintained consistent performance across varying temperature conditions, with 92% of punches in the "Good" category within this range. The larger surface area of this blade likely facilitated better heat distribution across the punching circumference, reducing localized temperature variations that could affect hole quality.

The 10cm diameter blade required significantly higher temperatures for optimal performance (240-255°C). The increased thermal mass of the larger blade and greater circumference necessitated higher energy input to achieve complete melting through the plastic. At temperatures below 235°C, punching was consistently incomplete, while temperatures above 260°C resulted in excessive melting and deformation of the surrounding mulch area.

Thermal Efficiency Considerations:

The temperature differentials required for different blade sizes align with fundamental heat transfer principles. The energy requirement (Q) for melting follows the $Q = M \times C \times \Delta T$, where the effective mass (M) of plastic being melted increases proportionally with blade diameter. The 8cm blade appears to represent an optimal balance between thermal efficiency and mechanical effectiveness, requiring moderate temperatures while producing consistent results.

Evaluation of Blade Diameter Performance

Consistency and Reliability Analysis

Statistical analysis of the punching results across all experiments revealed significant differences in performance consistency between blade diameters (Table 1). The 8cm blade demonstrated superior consistency, with 87.2% of all punches rated "Good" across its optimal temperature range. In comparison, the 6cm and 10cm blades achieved 78.5% and 74.8% "Good" ratings respectively within their optimal ranges.

The enhanced performance of the 8cm blade can be attributed to its optimal surface-area-to-circumference ratio. This geometry likely promotes more uniform heat distribution throughout the cutting edge, reducing the occurrence of partial melting that plagued the smaller blade and excessive energy requirements that challenged the larger blade.

Agricultural Application Suitability

From a practical agricultural perspective, each blade diameter serves distinct planting requirements. The 6cm blade produces holes suitable for seedlings with smaller root balls, such as celery and certain leafy vegetables. The 8cm diameter accommodates most common vegetable transplants including tomatoes and eggplants, while the 10cm size is appropriate for larger plants such as watermelon and cabbage. The machine's ability to interchange blades provides valuable flexibility for diverse cropping systems.

Cutting Efficiency and Productivity Assessment

Quantitative Efficiency Metrics:

The machine achieved an overall cutting efficiency of 83% based on the ratio of actual to theoretical cutting rates. This efficiency rating demonstrates substantial improvement over manual punching methods, which typically achieve approximately 30-40% efficiency when accounting for operator fatigue, inconsistency, and setup time.

The theoretical cutting rate (R_input) was calculated as 3.0 m^2/minute, while the actual operational rate (R_output) averaged 2.5 m^2/minute during sustained operation. The efficiency reduction from theoretical maximum can be attributed to system acceleration/deceleration periods, temperature stabilization requirements, and material handling intervals.

Comparative Performance with Manual Methods:

In direct time-motion comparison, the automated machine completed 50 punching cycles in approximately 4 minutes, compared to 12-15 minutes for an experienced worker using manual methods. This represents a 67-75% reduction in processing time, with the additional advantage of perfect hole spacing consistency, which is rarely achieved through manual methods.

Energy Consumption and Power Utilization

Motor Performance Analysis:

The servo motor demonstrated an operational efficiency (η) of 2.24%, calculated from the ratio of mechanical power output (6.29W) to electrical power input (280.8W). This apparently low efficiency is characteristic of servo systems operating at partial load conditions and reflects the conservative motor sizing for this application. The motor was specified to handle potential future enhancements and heavier material loads.

The system maintained consistent linear mulch feed velocity of 1.048 m/s throughout operations, with positional accuracy within ±2mm, ensuring precise hole spacing as programmed through the HMI interface.

Thermal Energy Requirements:

Power consumption analysis for the heating system revealed variations according to blade diameter. The 6cm, 8cm, and 10cm blades required average power inputs of 11,100W, 10,975W, and 10,869W respectively to maintain optimal punching temperatures. The slightly higher energy requirement for smaller blades reflects their reduced thermal mass and consequent heat loss to the environment.

Ergonomic and Practical Implementation Considerations

The automated system successfully addressed the primary ergonomic challenges associated with manual mulch punching. Operators reported significantly reduced physical strain compared to manual methods, which typically require constant bending, repetitive arm motions, and hand tool manipulation. The machine's design eliminated these risk factors while maintaining simple operational requirements suitable for agricultural workers with varying technical backgrounds.

The modular aluminum frame construction facilitated easy transportation and set up in field conditions, while the integrated roller system simplified material handling compared to manual unrolling and positioning of mulch sheets.

Limitations and Technical Constraints

Several limitations were identified during testing:

1. The current heating system requires approximately 3-5 minutes to reach optimal operating temperatures from cold start, suggesting potential for improved thermal insulation or pre-heating strategies.
2. Punching consistency slightly decreased during extended continuous operation, possibly due to heat buildup in mechanical components.
3. The system demonstrated optimal performance with standard 0.3mm thickness polyethylene mulch, with thicker materials requiring parameter adjustments.

Comparison with Existing Technologies

When compared to previously documented mulch punching solutions [5,6,7], this PLC-controlled thermal punching system represents a significant advancement in automation level and precision. Unlike purely mechanical systems [7], the thermal punching mechanism produces cleaner edges without plastic tearing. The integration of servo motor control for precise material positioning exceeds the capabilities of previously described semi-automatic devices [5,6], while the programmable nature of the system allows for rapid adjustment to different planting configurations without mechanical modifications.

CONCLUSIONS AND RECOMMENDATIONS

In conclusion, this study successfully designed, constructed, and validated a fully automatic plastic mulch punching machine that integrates a PLC-based control system with a thermal punching mechanism. The machine demonstrated robust performance, achieving an impressive cutting efficiency of 83%. The 8 cm diameter punch blade was identified as the most effective, operating optimally within a temperature range of 194–234°C to produce consistent, high-quality holes. This automation presents a significant advancement over manual methods, offering superior speed, precision, and ergonomic benefits that can substantially enhance productivity in agricultural mulch preparation.

To transition this prototype into a viable product for end-users, several steps are recommended. Future work should prioritize the development of a non-thermal, mechanical cutting system to eliminate energy-intensive heating and broaden the machine's application. Furthermore, comprehensive field trials are essential to rigorously evaluate the machine's long-term durability, adaptability to various mulch materials and environmental conditions, and its overall economic viability for small to medium scale farming operations, ensuring it meets the practical needs and constraints of the agricultural sector.

FURTHER STUDY

A dedicated further study is proposed to investigate the replacement of the thermal punching mechanism with an energy-efficient, sharp mechanical blade system. This research should focus on analyzing the cutting forces required for different plastic mulch thicknesses, optimizing blade geometry to prevent plastic tearing, and conducting a comparative life-cycle cost analysis between the thermal and mechanical systems to determine the most sustainable and economically feasible solution for farmers.

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