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TECHNICAL FEASIBILITY ANALYSIS OF A SOLAR-POWERED AGRICULTURAL PRODUCE DRYER FOR STRENGTHENING THE RURAL ECONOMY IN SIMALUNGUN REGENCY

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Abstract
Postharvest handling of agricultural products in Simalungun Regency is still dominated by open sun drying, which is highly dependent on weather conditions, vulnerable to contamination, and often produces uneven levels of dryness. This study aims to analyze the technical feasibility of a solar-powered agricultural product dryer and its contribution to strengthening the rural economy. The study employed a descriptive qualitative approach, using primary data obtained through in-depth interviews and observations, as well as secondary data derived from technical documentation, production records, quality standards, and price information. Data were analyzed through data reduction, data display, conclusion drawing, and source triangulation. The findings indicate that the dryer was capable of increasing temperature, protecting products, accelerating moisture reduction, and improving product quality. However, its technical feasibility depended on equipment design, air circulation, load capacity, operator competence, and the governance of its utilization. The machine was therefore considered feasible for further development, provided that it is supported by adequate training, maintenance, and farmer-group management.

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1. INTRODUCTION

Simalungun Regency has a diverse agricultural production base, particularly maize, coffee, rice, chili peppers, candlenuts, and other commodities that require appropriate postharvest handling to prevent deterioration in quality and economic value before reaching the market. However, preliminary research data indicate that drying at the farm level is still largely conducted through open sun drying in yards, on tarpaulins, or along roadsides, making its effectiveness highly dependent on weather conditions and the intensity of solar radiation. This situation is consistent with findings that open sun drying tends to be slow, requires intensive supervision, and increases the likelihood of products being exposed to soil, insects, dust, and other sources of contamination during moisture removal (Afzal et al., 2023). The instability of solar radiation also makes it difficult to maintain a consistent drying temperature, resulting in variations in the rate of moisture release, drying uniformity, color, and final product quality across different layers and drying periods (Rulazi et al., 2023). Meanwhile, the use of electricity- or fuel-powered mechanical dryers creates challenges related to investment, energy, and maintenance costs, which are not always affordable for smallholder farmers. In contrast, low-cost solar dryers can increase the temperature inside the drying chamber while accelerating moisture reduction compared with open sun drying (Hossain et al., 2025). These realities demonstrate that drying is not merely a technical matter but a critical stage that determines postharvest losses, commodity quality, selling prices, the sustainability of agricultural household income, labor efficiency, and the economic resilience of rural communities.

Recent literature shows that the development of solar drying machines has produced various configurations, including direct, indirect, mixed-mode, and hybrid systems. Nevertheless, these design advancements have not fully addressed the practical needs of farmers in rural contexts. Previous studies have largely focused on dryer classifications, airflow mechanisms, thermal energy storage, thermal efficiency, and energy and exergy analyses, whereas the relationships among technical performance, economic feasibility, market orientation, and user needs have not been examined in a balanced manner (Ndukwu et al., 2023). Studies on indirect solar dryers also indicate that their effectiveness depends on collector configuration, drying chamber design, airflow patterns, heat storage, material capacity, and operating conditions. However, no single universal design is automatically suitable for all environments, commodities, and production scales (Shekata et al., 2024). The intermittent nature of solar energy remains a fundamental limitation because fluctuations in radiation can lead to inadequate drying and reduced product quality. Therefore, indicators such as maximum temperature, drying time, efficiency, water extraction rate, and energy requirements must be evaluated in an integrated manner (Venkateswarlu & Reddy, 2024). At the same time, the socioeconomic impacts of solar dryers, including cost reduction, increased profitability, job creation, and reduced postharvest losses, remain less extensively documented than their technological development (Kimaro et al., 2024). This gap highlights the need for research that integrates machine performance, product quality, farmer acceptance, and rural economic strengthening within a contextual feasibility framework.

Based on these empirical problems and gaps in the literature, this study aims to analyze the technical feasibility of a solar-powered agricultural product drying machine to support postharvest activities among farming communities in Simalungun Regency. The analysis initially focuses on identifying the constraints associated with conventional drying methods, followed by an assessment of the machine’s construction, capacity, heat absorption system, airflow distribution, drying chamber temperature, safety, and ease of operation as key elements determining its functionality. Parameters such as thermal efficiency, drying rate, processing time, maximum temperature, and heat retention capacity are essential because modifications to solar radiation capture configurations and reductions in heat loss have been shown to produce significant differences in dryer performance (Jain et al., 2023). This study also measures moisture content reduction, compares the quality of solar-dried products with conventionally sun-dried products, and identifies operational and maintenance constraints, considering that the integration of thermal storage can improve heat supply, efficiency, drying rate, and process completion under fluctuating radiation conditions (Gilago et al., 2023). Load capacity is also analyzed because the literature shows that solar dryer capacities vary considerably, while a mismatch between machine size and commodity volume may inhibit uniform heat distribution and limit technology utilization at the farmer-group level (Kidane et al., 2024). Furthermore, the study evaluates the machine’s potential contribution to reducing postharvest losses, improving product quality and selling value, and formulating development recommendations that correspond to commodity characteristics, environmental conditions, and the management capabilities of local farmers through either individual or collective utilization schemes.

This study is important because the feasibility of a solar drying machine cannot be determined solely by its ability to generate hot air. Instead, it must be demonstrated through the compatibility among technical design, climatic conditions, commodity type, production capacity, product quality, operating costs, and user capabilities. Theoretically, solar dryers offer faster drying rates, improved product quality, and lower energy costs. However, the interactions among the collector, drying chamber, airflow, heat transfer, and moisture diffusion determine whether these benefits can actually be achieved under field conditions (Nnamchi et al., 2025). Recent technological developments have even shifted toward hybrid systems, energy storage, computational modeling, and intelligent control. Nevertheless, adoption continues to be constrained by inconsistent efficiency, weather variability, and limitations in scalable designs (Mohammed et al., 2026). From the user perspective, technology acceptance is influenced by perceptions of drying speed, product quality, and marketing opportunities. Therefore, technical evaluation must be linked to the economic benefits actually experienced by farmers (Kumi et al., 2023). In addition, affordability, the use of local materials, training, access to financing, ease of maintenance, and institutional support are important factors in expanding the adoption of solar dryers among smallholder farmers (Salvador et al., 2025). Accordingly, this study argues that a solar-powered

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drying machine will be feasible and capable of strengthening the rural economy when its thermal performance is stable, product quality is improved, operation is simple, capacity is appropriate, and its management can be implemented collectively and sustainably.

2. RESEARCH METHOD

The object of this study is the technical feasibility of a solar-powered agricultural product dryer within the context of postharvest handling among rural communities in Simalungun Regency. The phenomena examined include farmers' dependence on open sun drying, uncertainty in drying duration due to changing weather conditions, uneven moisture content, contamination risks, and limited financial capacity to use fossil fuel- or electricity-powered drying machines. The study also focuses on the machine's ability to generate and maintain drying temperatures, distribute hot air, reduce moisture content, accelerate the drying process, preserve product cleanliness, and operate in accordance with farmers' production capacity. These characteristics were observed under naturally occurring operating conditions without experimental treatment or manipulation of either technical variables or user behavior. This approach enables the researcher to describe the relationships among equipment construction, solar radiation intensity, material thickness, rack position, air circulation, operator skills, and product quality as they naturally occur during the drying process. Qualitative description is intended to provide a direct and rich account of experiences or events, remain close to participants' data, and examine phenomena in their natural settings without predetermining or manipulating variables (Hall & Liebenberg, 2024). By defining the research object in this manner, the study is not intended to establish causal predictions but rather to obtain a comprehensive understanding of the suitability of solar drying technology for the technical, operational, and agricultural environmental needs of Simalungun Regency.

This study employs a descriptive qualitative research design because its primary focus is to gain an in-depth understanding of the experiences, assessments, actions, and actual conditions associated with the use of solar-powered agricultural product dryers. A qualitative approach was selected to explain how farmers conduct conventional drying, how operators use the machine, how technicians assess its construction and performance, and how stakeholders perceive the benefits of the technology for product quality and the rural economy. Qualitative research enables the exploration of context, perspectives, and human interactions through open-ended questions, in-depth interviews, and direct observation, making it appropriate for understanding complex phenomena that cannot be adequately reduced to numerical measurements alone (Lim, 2025). Primary data were obtained through interviews with informants concerning weather-related constraints, drying duration, moisture reduction, heat distribution, load capacity, product cleanliness, ease of operation, maintenance, costs, and market acceptance. These primary data were complemented by observations of open sun drying practices and machine operation in the research setting. Secondary data were collected from journal articles, agricultural production documents, farmer group profiles, solar radiation and rainfall data, agricultural equipment assistance programs, commodity quality standards, and price information based on moisture levels. The secondary literature focused on three main keyword areas: agricultural product dryers, solar energy, and the rural economy, thereby ensuring that the empirical explanation remained connected to scientific developments and the context of technology application.

Research participants were selected purposively based on their direct involvement, knowledge, experience, and position in agricultural activities, postharvest drying, machine development, product marketing, and rural development. Purposive selection enables researchers to identify informants capable of providing rich and relevant information related to the research focus, while participant adequacy is determined by the depth of the data and the recurrence of information rather than merely by the number of respondents (Bouncken et al., 2026). The first informant was a farmer who used the drying machine, while the second was a farmer who continued to apply conventional drying methods. The third informant was the head of a farmer group, the fourth was the machine operator, and the fifth was the machine designer or technician. The sixth informant was an agricultural extension officer, the seventh was a trader or agricultural produce collector, the eighth was a representative of the Simalungun Regency Agricultural Office, the ninth was a village government official, and the tenth was an academic or expert in mechanical engineering and renewable energy. This diversity of positions was intended to capture the perspectives of technology users, managers, developers, farmer facilitators, product buyers, government representatives, and experts. Participant selection procedures in qualitative research should be aligned with the objectives, problems, and context of the study so that the experiences collected are sufficiently in-depth and directly related to the phenomenon being analyzed (Dahal et al., 2024). Informants' identities may be presented using codes such as PT-01, KT-01, OP-01, and TK-01 to maintain confidentiality while facilitating the traceability of data sources during analysis.

The research process was conducted through the stages of preparation, field data collection, evidence organization, and an initial examination of information completeness. During the preparation stage, the researcher determined the research location, established informant criteria, developed the interview guide, prepared the observation sheet, and identified documents related to agricultural product drying and the use of solar energy. Data were collected through in-depth interviews, participant observation, and documentation because these three techniques can capture verbal explanations, actual practices, and visual or administrative evidence concerning the same phenomenon. Recent methodological literature explains that interviews, participant observation, and document analysis are major techniques in qualitative research that can be used complementarily to obtain a more comprehensive and nuanced understanding of social realities (Surawy-Stepney et al., 2023). The interviews focused on drying experiences, machine performance, product quality, equipment management, costs, constraints, and opportunities for adoption. Observations were conducted on open sun drying conditions, collector construction, drying chamber design, rack arrangement, airflow, temperature, material thickness, product-turning practices, and changes in the physical characteristics of the products. Documentation included photographs of the equipment and activities, temperature and humidity records, initial and final weights, moisture content, load capacity, weather conditions, production data, and quality standards. Each interview was recorded or documented with the informant's consent, subsequently transcribed and coded, while observational notes and documents were classified according to technical, operational, quality, and economic dimensions so that all evidence could be analyzed systematically.

Data analysis employed the interactive model of Miles and Huberman, which was implemented from the beginning of data collection until the emerging patterns were considered sufficiently developed. The first stage was data reduction, which involved reading interview transcripts, observation notes, and documents, selecting relevant information, simplifying the descriptions, assigning codes, and grouping the data into themes such as conventional drying constraints, temperature, heat distribution, moisture content, capacity, quality, operation, maintenance, and economic benefits. The second stage involved presenting the data in the form of narratives, comparative matrices, technical parameter tables, and relationships among categories so that similarities, differences, and emerging tendencies could be easily traced. The application of the Miles and Huberman model positions data reduction, data display, and conclusion drawing or verification as a systematic sequence for organizing interview, observation, and documentary data into interpretable findings (Ardiputra et al., 2025). The third stage involved drawing provisional conclusions, which were continuously tested against additional evidence, contrasting cases, and explanations from other informants until consistent findings were obtained. Data validity was examined through source triangulation by comparing, correlating, and confirming information provided by farmers, operators, technicians, farmer groups, extension officers, traders, government officials, and academics. Triangulation was used to identify recurring patterns and verify findings through comparisons of data or analytical results derived from different sources (Arias Valencia, 2022). The final conclusions were established after the interview data, participant observations, and documentation demonstrated a logical relationship between the machine's technical feasibility and its implications for the rural economy.

3. RESULT AND ANALYSIS

Performance of the Agricultural Produce Dryer

The performance of the solar-powered agricultural produce dryer at the research site was described through its construction, operating process, temperature changes, hot-air distribution, material placement, and drying results observed during field activities. The machine consisted of a heat-absorbing collector, air ducts, an enclosed drying chamber, material racks, a door, ventilation openings, a humid-air exhaust outlet, and a temperature-measuring instrument, where available. Interviews with farmers who used the dryer or participated in its trial indicated that the enclosed drying chamber provided better protection because the materials did not come into direct contact with the ground and were less exposed to dust or animals. During operation, the temperature inside the drying chamber was perceived to be higher than the ambient temperature after the collector was exposed to sunlight. Observations also recorded that the temperature increased gradually, while its stability varied according to solar radiation conditions. The products were arranged on multilevel racks to use the available space more efficiently; however, the thickness of the material layers and the distance between racks had to be carefully regulated during loading. The research documentation presented the physical form of the machine, the arrangement of its components, the placement of materials before the drying process began, temperature measurements, and the condition of the products after drying. Based on the overall data, the machine's performance was reflected in its ability to provide a protected drying environment, generate a drying temperature above ambient conditions, and directly support a more controlled moisture-reduction process.

Concise Informant Statement-Farmer Using or Participating in the Dryer Trial:

"According to farmers who used or participated in the trial of the solar-powered dryer, the enclosed drying chamber was considered capable of providing better protection for the products."

Data concerning the dryer's performance were further described through the heat-transfer and airflow stages occurring during operation. The collector received solar radiation and converted it into heat, after which the heated air moved toward the drying chamber through natural airflow or with the assistance of a fan. The hot air passed over the surface of the materials arranged on the racks, absorbed their moisture, and then carried the humid air toward the exhaust outlet. The operator monitored material loading, chamber temperature, drying duration, the need to turn the products, and the condition of the materials on each rack. Observations showed that materials arranged in thin and even layers achieved more uniform drying than materials stacked too thickly. Racks located closer to the hot-air pathway also appeared to undergo faster drying than racks receiving lower airflow. When the load exceeded the machine's capacity or the materials obstructed the airflow passage, some products dried earlier, while others retained relatively high moisture content. Inspections of the door, drying-chamber joints, air ducts, fan, and measuring instruments were conducted to prevent heat loss and airflow disruption. Documentary records included ambient temperature, collector temperature, chamber temperature, initial and final weights, moisture content, load capacity, and weather conditions. This series of observations demonstrated that the machine's performance was closely related to orderly loading, unobstructed air circulation, and operator monitoring throughout the drying process.

Concise Informant Statement-Dryer Operator:

"The machine operator explained that the dryer's performance was influenced by solar radiation intensity, heat-collector design, air circulation, the thickness of the materials being dried, load capacity, and the frequency with which the products were turned."

The description of the dryer's performance was directly related to the reality of postharvest handling, which remained dominated by open sun drying in the research area. Under conventional methods, agricultural commodities were placed on tarpaulins or simple mats in layers whose thickness was not always uniform and were then manually turned so that all parts received sunlight. When weather conditions changed, farmers had to immediately gather, cover, or move the products to a protected location to prevent them from being exposed to rain. Repeated movement required labor and continuous supervision and was accompanied by the possibility of products being scattered or exposed to dust, soil, insects, animals, and passing vehicles. The documentation illustrated the open nature of the drying locations and the absence of a designated space separating the products from the surrounding environment. Compared with these conditions, the dryer provided an enclosed chamber, multilevel racks, air ducts, and a heat-collection system that allowed the process to continue without the materials coming into direct contact with the ground. Field data also recorded that conventional drying took longer when solar intensity was low, whereas the drying chamber still experienced an increase in temperature after the collector received solar radiation. Although the machine's temperature remained influenced by weather conditions, loading, monitoring, and product turning could be conducted within a more protected space. The relationship among these data situated the machine's performance within the principal research problem, namely the need for a drying process that was cleaner, more orderly, and not entirely dependent on open sun drying.

Concise Informant StatementFarmer Using Conventional Drying:

"The farmers stated that the method was easy to perform and did not require energy costs."

Utilization of Solar Energy

The utilization of solar energy in the dryer was described through the process by which the collector received solar radiation and transferred heat into the drying chamber. The machine technician or designer explained that the collector was the first component to receive solar radiation, while the transparent cover and absorber surface helped retain heat before the air was directed into the drying chamber. The heated air moved through the inlet duct, passed over the materials on each rack, and then exited through the ventilation opening or exhaust outlet after carrying moisture away from the products. Observations recorded an increase in chamber temperature after the collector was exposed to sunlight, particularly under clear weather conditions and high solar-radiation intensity. Under these conditions, the temperature appeared more stable, and the moisture-reduction process proceeded more rapidly. When the sky was overcast, the chamber temperature decreased, and a longer period was required to achieve the intended level of dryness. The research documentation included the collector position, the direction of the air ducts, the condition of the drying chamber, temperature-measuring instruments, and weather records during testing. The available data also included possible records of ambient temperature, collector temperature, relative humidity, and chamber temperature at different times. The entire description demonstrated that solar energy was used as the primary heat source without the direct combustion of fuel inside the machine. This energy source was utilized through the connection among the collector, heated air, drying chamber, material racks, and humid-air exhaust outlet.

Concise Informant Statement-Machine Technician or Designer:

"The machine technician or designer explained that the drying system utilized solar radiation received by the heat collector."

The explanation of the solar-energy data in this study was reflected in changes in the drying-chamber conditions throughout the period of solar exposure. At the beginning of operation, the collector began receiving solar radiation, and the air temperature within the system gradually increased. The heated air subsequently flowed toward the drying chamber, passed over the materials, and transported water vapor out through the ventilation system. The magnitude of the temperature increase was not always the same because it was influenced by solar intensity, cloud conditions, collector position, insulation level, duct dimensions, fan use, and the amount of material loaded. Under high solar radiation, the operator observed that the temperature was easier to maintain, whereas overcast conditions caused a temperature decrease followed by an extension of the drying period. Material placement also influenced the utilization of the available heat. Materials arranged in excessively thick layers obstructed the movement of air over the entire product surface, whereas thinner arrangements provided space for hot air to circulate more evenly. Documentation collected before and after the process showed changes in the materials' weight, texture, color, aroma, cleanliness, and level of dryness. Testing records were also prepared to document initial weight, final weight, initial moisture content, final moisture content, temperature, humidity, capacity, and weather conditions during each operation. During operation, solar energy was neither stored nor supplied at a constant intensity; therefore, weather changes were directly reflected in the chamber temperature. These data provided an overview of the sequence of energy utilization, beginning with the receipt of solar radiation by the collector and ending with the removal of moisture from the drying chamber.

Concise Informant Statement-Machine Technician or Designer:

"The effectiveness of the system was determined by the collector's capacity to absorb heat, the stability of the airflow, the insulation level of the drying chamber, and the dimensions and positions of the air inlet and outlet ducts."

The utilization of solar energy was associated with the research problem concerning the dependence of agricultural-product drying on weather conditions and the limited ability to use high-cost energy sources. In conventional sun drying, the materials received sunlight directly without a heat-collection chamber, meaning that changes in cloud cover, rainfall, and solar-radiation intensity immediately affected the product surfaces. Farmers had to wait for clear weather, turn the materials, and move them when weather conditions changed. The dryer used a collector to receive solar radiation and direct heated air into an enclosed chamber, thereby preventing the materials from being placed directly in an open area. Interview findings indicated that farmers considered the cost of the equipment, ease of use, availability of spare parts, capacity, maintenance requirements, and compatibility of the machine with particular commodities. Observations recorded that solar energy was capable of increasing the chamber temperature, although the magnitude of the increase continued to vary according to radiation conditions. Under overcast conditions, the drying period still increased, while the need for an alternative heat source was identified as an aspect requiring consideration in the machine's further development. Documentation of the machine's construction showed that energy utilization occurred without a fuel-combustion chamber, with the principal components consisting of a collector, air ducts, drying chamber, racks, and ventilation openings. The relationship among these data demonstrated that solar energy was used to reduce dependence on electricity or fuel during the drying process. Nevertheless, its operation continued to require appropriate regulation of the design, capacity, circulation system, and adaptation to weather changes in Simalungun Regency during postharvest activities.

Concise Informant Statement-Agricultural Extension Officer:

"The agricultural extension officer stated that farmers' acceptance of the technology was not determined solely by the machine's ability to dry agricultural products."

Rural Economy

The condition of the rural economy in this study was described through the relationship among the drying process, agricultural-product quality, handling costs, equipment management, and product selling prices. The head of the farmer group stated that the solar-powered dryer could be used as a shared facility because procurement and maintenance costs could be collectively covered. Shared utilization required scheduling, operator appointment, recording of product quantities, distribution of maintenance costs, and assignment of responsibility in the event of damage. Farmers using the machine considered that the enclosed chamber protected the materials from dust, soil, and animals, while the higher temperature assisted the moisture-reduction process. Traders or agricultural produce collectors identified moisture content, color, cleanliness, aroma, and uniformity as factors considered when determining purchase prices. Products with high moisture content tended to receive lower prices because of the risk of weight loss and deterioration during storage. Observations recorded that materials arranged in thin and even layers achieved more uniform drying, while documentation showed changes in their physical condition before and after the process. The agricultural extension officer also stated that technology acceptance was influenced by equipment price, capacity, maintenance requirements, spare-part availability, and operator training. The supporting data collected included commodity production, farmer-group profiles, equipment-assistance programs, quality standards, and prices based on moisture content. Collectively, these data described the rural economic elements associated with the use of the dryer at both the individual farmer and farmer-group levels.

Concise Informant Statement-Head of the Farmer Group:

"The head of the farmer group considered that the solar-powered dryer had the potential to be used as a shared facility."

The explanation of the rural economic data was evident in the sequence of activities beginning when products were harvested and continuing until they were received by traders or collectors. Under open drying methods, farmers had to provide tarpaulins, prepare the drying location, turn the materials, monitor changing weather conditions, and move the products when rain or overcast conditions occurred. Delayed drying could cause the products to retain high moisture content and experience changes in color, odor, fungal growth, or cleanliness, all of which were considered during the purchasing process. The dryer altered parts of this sequence through the use of an enclosed chamber, multilevel racks, heated airflow, and temperature monitoring. The use of racks enabled the materials to be placed on several levels, while the enclosed chamber reduced direct contact with the surrounding environment. At the farmer-group level, equipment use could be scheduled according to the production volume of each member and operated by an individual who understood the procedures for loading, turning, measuring, and cleaning. Procurement and maintenance costs could be shared, although such arrangements required mutually agreed rules. The availability of replacement components and the capacity to perform regular inspections were also part of equipment utilization. Traders assessed products based on moisture content, uniformity, color, aroma, and cleanliness before determining the purchase price. Price documentation and quality standards could be compared with records of initial weight, final weight, moisture content, and drying duration. This series of data explained how the technical drying process was recorded alongside labor activities, group management, equipment maintenance, and market acceptance in rural areas on a continuing basis.

Concise Informant Statement-Trader or Agricultural Produce Collector:

"The trader or agricultural produce collector stated that moisture content, color, cleanliness, aroma, and product uniformity were factors influencing the purchase price."

The relationship among machine performance, solar-energy utilization, and the rural economy was evident in the postharvest handling process experienced by farmers in Simalungun Regency. The machine provided an enclosed drying chamber that received heated air from the collector, while the products were placed on racks at regulated thicknesses and distances. Under high solar-radiation conditions, the chamber temperature increased and became more stable, whereas overcast weather reduced the temperature and extended the drying period. The operator had to regulate load capacity, product turning, temperature monitoring, and component cleanliness to maintain continuous airflow. Products dried inside the enclosed chamber were better protected from soil, dust, insects, animals, and rain than products dried in open spaces. In terms of marketing, moisture content, color, aroma, cleanliness, and uniformity were characteristics considered by traders or collectors. In terms of management, farmer groups considered shared utilization, distribution of maintenance costs, scheduling, product recording, operator appointment, and responsibility for damage. The agricultural extension officer noted the need for training, technical assistance, spare parts, capacity appropriate to the commodity, and ease of use. The research documentation compiled information on equipment conditions, drying data, product changes, quality standards, commodity production, equipment-assistance programs, and prices. The relationship among all these data described the position of the solar-powered dryer as part of the technical activities, group management, quality handling, and marketing of agricultural products in the rural areas of Simalungun Regency.

Concise Informant Statement-Farmer Using Conventional Drying:

“Farmers also stated that open drying involved a risk of contamination by dust, soil, insects, animals, and passing vehicles when the products were dried near roads.”

Discussion

The findings indicate that the technical feasibility of the solar-powered dryer in Simalungun Regency is conditional rather than automatically inherent in the mere presence of a collector and drying chamber. Evidence obtained from interviews, observations, and documentation shows that the enclosed chamber can increase the temperature above ambient conditions, protect agricultural commodities from dust, soil, insects, animals, and rainfall, and create a more controlled moisture-reduction process. However, these benefits diminish when the load exceeds the machine’s capacity, the materials are arranged in excessively thick layers, the distance between racks obstructs air circulation, or the operator fails to conduct appropriate monitoring and product turning. Therefore, the machine’s feasibility is determined by the interaction among collector construction, airflow distribution, solar-radiation intensity, actual load capacity, operator competence, component maintenance, and commodity characteristics. This assessment is consistent with research indicating that solar-dryer performance should be evaluated through a combination of chamber temperature, drying time, final moisture content, product quality, efficiency, and economic feasibility rather than solely through an increase in temperature (Rana et al., 2024). The findings also position economic benefits as a consequence of successful technical performance: cleaner products with more uniform quality may improve market acceptance, but such benefits can only be achieved when the equipment is operated within its designated capacity, competent operators are available, and maintenance costs can be distributed proportionally. Accordingly, the research objective of assessing performance, constraints, product quality, and economic contribution is addressed through the substantive conclusion that the machine is feasible for further development, provided that clearly defined technical and institutional prerequisites are fulfilled.

From a discursive perspective, these findings are related to previous studies emphasizing the advantages of enclosed drying chambers over open sun drying, while offering a more contextually grounded scope of evaluation. A study on bottle gourd found that an indirect dryer protected the product from direct radiation, dust, insects, and contamination while maintaining better color, although its drying rate did not always exceed that of direct sun drying under certain conditions (Al-Ghadani et al., 2024). This finding reinforces the results obtained in Simalungun, indicating that the advantages of the machine are not limited to drying duration but also include hygiene, process controllability, and quality consistency. Other research has shown that temperature, humidity, and airflow velocity inside a drying chamber may differ according to position, meaning that uniform heat distribution requires measurable duct design and airflow regulation (Chouikhi & Amer, 2023). Compared with these experimental studies, the strength of the present research lies in its integration of technical assessment with user experience, farmer-group management capacity, market requirements, and rural economic conditions. Comparisons among various drying methods also demonstrate that each configuration produces different outcomes depending on the product type, temperature, and convection system, indicating that no single technology is superior under all conditions (Radhakrishnan et al., 2024). This approach is important because the effectiveness of technology at the farmer level is simultaneously determined by its technical and social suitability. Thus, this study expands the discussion from the question of “whether the equipment works" to the question of "under what conditions the equipment can operate effectively, be accepted by farmers, and generate added value for rural areas."

Reflection on the findings shows that the principal benefit of the solar dryer lies in its capacity to transform postharvest handling from an activity that reacts to weather conditions into a more manageable process. Under open sun drying, farmers must adjust their work to changes in cloud cover and rainfall, repeatedly move the materials, and accept the risk of uneven moisture content. In contrast, the collector, enclosed chamber, racks, and ventilation system allow heat to be collected, directed, and utilized in a more structured manner, although its intensity remains influenced by solar exposure. Recent technical studies confirm that advances in solar dryers are determined by collector design, chamber geometry, airflow mechanisms, thermal storage, and control systems, which collectively influence efficiency and product quality (Villagran et al., 2024). This reflection indicates that the purpose of the study is not merely to test a piece of equipment but to identify intervention points capable of improving commodity quality, reducing losses, and strengthening farmers' bargaining position. Socioeconomic reviews have also found that solar dryers have the potential to save time, reduce operating costs, increase profitability, and decrease dependence on traditional energy sources, although their impacts are highly dependent on the context of use and the availability of adoption support (Kimaro et al., 2024). In the Simalungun context, these benefits are reflected in opportunities for collective utilization by farmer groups, shared maintenance costs, and the production of commodities with moisture levels that better meet market requirements. Therefore, the significance of this study lies in providing an empirical foundation for connecting technical design with farmers' actual needs rather than merely confirming that solar energy can generate heat.

The implications of the findings encompass machine design, agricultural extension, farmer-group institutions, equipment-assistance policies, and postharvest enterprise development. At the design level, the machine should be adapted to the dominant commodities, harvesting volume, material-layer thickness, rack distribution, and local solar-radiation patterns so that increased temperature does not result in uneven drying. At the operational level, indicators of success should include initial and final moisture content, temperature, humidity, drying duration, effective capacity, additional energy consumption, quality uniformity, and the frequency of component failure. The development of automated photovoltaic-thermal systems demonstrates that airflow regulation and monitoring can accelerate the achievement of equilibrium moisture content while providing economic benefits; however, system complexity also requires greater investment and maintenance capacity (Elwakeel et al., 2025). At the adoption level, the findings suggest that providing equipment without training, assistance, and a management scheme risks creating unsustainable utilization. Research involving smallholder farmers indicates that willingness to adopt solar-powered postharvest technologies is influenced by business profitability, previous experiences of crop losses, access to extension services, training, perceived benefits, and farming conditions (Kansanga et al., 2025). The policy implication is that machinery-assistance programs should be designed as integrated technological and institutional packages that include farmer-group selection, operator training, operating procedures, maintenance funds, performance recording, and linkages with buyers. Accordingly, the findings may serve as a basis for designing postharvest programs that assess success according to equipment functionality and product-quality improvement rather than merely the number of units distributed.

The findings emerged in this manner because drying constitutes a heat- and mass-transfer system simultaneously influenced by environmental conditions, equipment design, material characteristics, and user behavior. Solar-radiation intensity determines the amount of energy received by the collector, while insulation and component joints determine the quantity of heat that can be retained before the air enters the drying chamber. Subsequently, airflow velocity and direction determine the ability of heat to reach all racks and transport water vapor out of the chamber. When materials are stacked too thickly or the machine's capacity is exceeded, the surface area exposed to the air decreases and airflow resistance increases, causing some materials to release moisture more rapidly than others. Research on solar dryers employing multiple airflow systems demonstrates that equipment configuration influences radiation capture, air temperature, moisture evaporation, and thermal performance, meaning that construction design cannot be separated from drying outcomes (Elmsaad et al., 2024). Variations in outcomes also occur because each commodity has different initial moisture content, dimensions, tissue structure, and sensitivity to quality deterioration. Food-preservation research confirms that controlled drying can extend shelf life and increase added value, whereas inappropriate temperature and duration may alter color, texture, and specific quality components (Amissah et al., 2025). Human factors explain why a structurally adequate machine may not necessarily produce stable performance: operators must regulate loading, product turning, temperature, cleanliness, and maintenance. Therefore, the findings are a logical consequence of the interrelationship among thermal factors, material characteristics, weather conditions, and users' management capacity.

Based on the findings, the necessary course of action is to implement gradual development through technical testing, field demonstrations, and strengthened farmer-group management. The first stage should involve standardized measurements of ambient, collector, and drying-chamber temperatures; humidity; initial and final moisture content; drying duration; effective capacity; inter-rack uniformity; and the physical quality of each commodity. These data are required to determine the most appropriate duct configuration, rack spacing, material-layer thickness, and load limit. The second stage involves improving performance stability through better insulation, ventilation regulation, solar-powered fans, easily readable measuring instruments, and, where necessary, thermal storage or hybrid energy sources to address overcast weather conditions. These technological improvements should be implemented proportionally so that the addition of components does not make the machine excessively expensive, difficult to repair, or dependent on spare parts unavailable near the user community. The third stage involves establishing a farmer-group governance system that determines operators, schedules, usage fees, maintenance funds, commodity records, and procedures for handling equipment damage. Research on the adoption of solar dryers among smallholder farmers indicates that compatibility with local needs, affordability, access to financing, training, and user participation in technology development are essential conditions for wider adoption (Viola Salvador et al., 2025). The final action is to connect farmer groups with agricultural extension officers, technicians, village governments, agricultural agencies, and buyers so that moisture-content and quality standards become the basis for operational practices and selling-price determination.

4. CONCLUSION

The most surprising finding of this study is that the technical feasibility of a solar-powered agricultural produce dryer is not primarily determined by the amount of heat it can generate, but rather by the integration of equipment design, airflow patterns, load capacity, operator competence, and the governance of its utilization. The machine was indeed capable of creating a more protected drying environment, increasing the temperature above ambient conditions, accelerating moisture removal, and protecting products from dust, soil, insects, animals, and rainfall. However, these benefits may diminish when materials are stacked too thickly, racks are arranged without considering airflow distribution, the load exceeds the machine's capacity, or temperature monitoring and product turning are not performed consistently. In other words, equipment that is physically operational does not necessarily produce uniform drying and optimal final product quality. This study also found that economic benefits do not automatically result from the use of solar energy; rather, they emerge when the technical quality of the drying process is successfully translated into appropriate moisture content, improved cleanliness, lower product shrinkage, and greater market acceptance. This finding shifts the understanding of solar dryers from merely heat-generating devices to postharvest systems requiring design precision, operational discipline, and effective institutional management. Therefore, the feasibility of the dryer in Simalungun Regency should be understood as the outcome of the simultaneous compatibility of the technology with commodity characteristics, environmental conditions, user capabilities, and farmer organizations.

The added value of this study lies in its contribution to connecting the technical dimensions of the machine with the socioeconomic realities of rural areas within an integrated analytical framework. Theoretically, the study broadens the understanding that the feasibility of solar drying technology cannot be adequately assessed solely through indicators of temperature, drying time, or moisture-content reduction. Instead, it should be examined through the relationships among thermal performance, product quality, user behavior, institutional capacity, and market response. This perspective enriches the fields of mechanical engineering and renewable energy by incorporating technology adoption, farmer-group governance, and postharvest added value as integral components of technical success. Practically, the findings provide a foundation for machine designers to improve collector design, insulation, ventilation, rack spacing, effective capacity, and temperature-monitoring systems in accordance with the characteristics of local commodities. For farmer groups, this study offers a basis for establishing shared-use mechanisms through scheduling, operator appointment, load recording, distribution of maintenance costs, and assignment of responsibility for equipment damage. For local governments and agricultural extension officers, the findings may be used to design equipment-assistance programs that extend beyond the distribution of machinery by incorporating training, technical assistance, performance evaluation, and strengthened market access. Thus, the principal contribution of this study is the formulation of a conceptual model in which solar drying technology delivers its full benefits only when technical innovation, user capabilities, institutional support, and rural economic needs are developed within a mutually reinforcing implementation system.

The limitations of this study are primarily associated with the scope of observation, which focused on the operating conditions of solar-powered dryers in Simalungun Regency and on qualitative data obtained from interviews, observations, and documentation. This focus enabled the study to produce an in-depth contextual account, but it did not include repeated experimental testing across all commodity types, seasons, weather variations, and technical configurations that may be applied in other regions. Data on temperature, humidity, moisture content, drying duration, effective capacity, additional energy consumption, and changes in physical quality also need to be expanded through standardized measurements conducted over a longer period so that the machine's performance patterns can be compared in greater detail. Furthermore, this study did not longitudinally assess changes in farmers' income, reductions in postharvest losses, equipment life-cycle costs, return on investment, or the sustainability of farmer-group management after the machine had been used over the medium and long term. These limitations provide opportunities for future research to integrate qualitative approaches with technical experiments, economic analysis, and technology-adoption monitoring. Subsequent studies could compare different collector designs, airflow systems, thermal-storage mechanisms, or hybrid energy sources across various commodities while simultaneously examining their effects on quality, costs, and selling prices. Such research directions are expected to generate design standards and implementation models that are more adaptive, measurable, and replicable across diverse rural agricultural regions.

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