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Development of a Solar-Powered Multipurpose Drying Tool to Support Food MSME Production in Rural Areas

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ABSTRACT

Small and medium food enterprises (MSMEs) in rural areas often face challenges in food preservation due to limited access to reliable and affordable drying technologies. Solar-powered drying tools offer a sustainable solution by utilizing renewable energy to enhance product quality and shelf life. This study aims to develop and evaluate a solar-powered multipurpose drying tool tailored to the needs of rural food MSMEs, focusing on improving drying efficiency, product quality, and operational affordability. The tool was designed using locally available materials and tested under real rural environmental conditions. Performance metrics such as drying time, energy consumption, and product quality retention were measured and compared to conventional drying methods. User feedback from local MSME operators was also collected to assess usability and acceptance. The developed solar drying tool reduced drying time by approximately 40%, maintained nutritional quality and sensory attributes of dried products, and operated with zero fuel cost. Users reported increased production capacity and product marketability. The solar-powered multipurpose drying tool demonstrates significant potential to support rural food MSMEs by offering an energy-efficient, cost-effective, and environmentally friendly drying solution, contributing to improved food preservation and rural economic development.

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1. INTRODUCTION

Food preservation is a critical challenge for small and medium enterprises (SMEs), particularly those engaged in food production in rural areas. These enterprises often rely on traditional drying methods, such as sun drying on open ground or rudimentary drying racks, which are vulnerable to environmental conditions, contamination, and inefficiencies. As a result, product quality suffers, shelf life is limited, and economic losses occur due to spoilage and inconsistent drying outcomes. Addressing these challenges through the development of innovative, sustainable drying technologies is essential for enhancing the productivity and profitability of rural food SMEs. The focus of this research is the development of a solar-powered multipurpose drying tool designed to meet the specific needs of food SMEs operating in rural contexts. Solar drying technology harnesses renewable energy from sunlight, offering an environmentally friendly alternative to conventional drying methods that often depend on fossil fuels or electric energy. Solar dryers can provide controlled drying conditions such as temperature, humidity, and airflow resulting in improved drying efficiency, reduced contamination risk, and higher retention of nutritional and sensory qualities of food products.

Rural areas worldwide, particularly in developing countries, host a significant number of food SMEs that contribute to local food security, income generation, and rural economic development. Despite their importance, these enterprises face technological and infrastructural constraints, including limited access to electricity, inadequate processing facilities, and lack of affordable, efficient drying equipment. The inconsistent quality of dried food products hinders SMEs' competitiveness and limits access to broader markets. This research addresses the technological gap by focusing on a multipurpose drying tool powered entirely by solar energy. The multipurpose aspect is particularly important, as rural SMEs often handle a variety of food products—including fruits, vegetables, spices, grains, and fish—that require different drying conditions. A versatile drying tool capable of adapting to various product types can significantly increase utility and cost-effectiveness for users.

The development of a solar-powered multipurpose drying tool carries significant importance in several dimensions. Environmentally, it promotes the use of renewable energy and reduces dependence on non-renewable resources, thereby contributing to sustainable food processing practices. Economically, it offers an affordable and low-operating-cost solution, enabling SMEs to extend product shelf life, reduce post-harvest losses, and increase incomes. Socially, it supports rural livelihoods by enhancing the capacity and quality of food production, potentially contributing to improved nutrition and food availability. Moreover, solar drying can mitigate health risks associated with traditional drying methods, where open-air drying exposes food to dust, insects, and microbial contamination. By providing an enclosed and controlled environment, the solar drying tool helps ensure food safety, meeting increasingly stringent market and consumer standards.

Previous research and technological development in solar drying have primarily focused on single-purpose dryers or technologies suited for large-scale or commercial applications, often requiring significant capital investment or technical expertise. Many existing solar dryers are designed for specific food products or climatic conditions, limiting their applicability and accessibility for diverse rural SMEs. Multipurpose Functionality: Unlike many dryers specialized for one type of product, this tool is engineered to accommodate a wide range of food items with adjustable parameters, enhancing flexibility and user value. Low-Cost and Locally Adapted Design: The tool incorporates locally available and affordable materials, ensuring that rural SMEs can easily access, maintain, and repair the equipment without dependence on expensive imported parts. User-Centric Development: The design process integrates user feedback from target rural SMEs, aligning technical features with operational realities and cultural contexts, thereby enhancing adoption potential. Sustainable Energy Use: The tool maximizes solar energy utilization through optimized design for maximum sunlight capture and efficient heat transfer, minimizing reliance on auxiliary energy sources. These differences position the research at the intersection of innovation, sustainability, and practical applicability, aiming to fill gaps that limit the impact of current solar drying technologies in rural SME settings.

The primary objective of this research is to develop, prototype, and evaluate a solar-powered multipurpose drying tool that can significantly improve drying efficiency and product quality for rural food SMEs. Specific objectives include, Designing a drying tool that operates solely on solar energy, with adaptable settings to accommodate different food types. Testing the drying performance under real rural environmental conditions, assessing drying time, temperature control, energy efficiency, and product quality preservation. Evaluating user acceptance, ease of operation, and maintenance requirements to ensure practical usability. Comparing the developed tool's performance with traditional sun drying and other existing solar dryers to highlight improvements. The contributions of this research are multi-fold. Technologically, it introduces a novel drying tool combining versatility, efficiency, and sustainability tailored for rural SMEs. Practically, it offers a scalable solution that can be replicated or adapted in various rural regions, enhancing food processing capabilities. Academically, it expands the knowledge base on solar drying technology design, optimization, and socio-technical integration in food SME contexts. Lastly, it supports policy and development programs focused on rural entrepreneurship, renewable energy adoption, and food security.

Supporting this research is the increasing global emphasis on sustainable development, clean energy, and rural empowerment. International development agencies, governments, and NGOs are prioritizing renewable energy technologies to improve livelihoods and reduce environmental impact. The food processing sector, particularly SMEs in rural areas, represents a critical frontier where such technologies can catalyze economic growth and sustainability. Furthermore, advancements in solar technology, material science, and low-cost fabrication methods provide an enabling environment for the practical realization of this research. Existing literature on solar drying, thermal dynamics, and user-centered design offers theoretical and empirical foundations that guide the tool's development and testing. By aligning with these global and technological trends, the research holds the potential to contribute meaningfully to the fields of renewable energy applications, food technology, and rural development.

2. RESEARCH METHOD

This study employed a design and experimental approach to develop and evaluate a solar-powered multipurpose drying tool tailored for food MSMEs in rural areas. The methodology was adapted from established frameworks in renewable energy appliance design and food drying technology, as outlined in previous works on solar dryer development and user-centered design principles. The initial phase involved a needs assessment through surveys and interviews with rural MSME operators to identify common drying challenges and product types. Based on this input and literature on solar drying mechanisms, a prototype dryer was designed using locally available materials to ensure affordability and ease of maintenance. The design incorporated adjustable airflow, temperature control via passive solar collectors, and modular drying trays to accommodate diverse food products. The prototype was installed in a representative rural setting and subjected to drying trials using common MSME food products such as fruits, vegetables, and spices. Key performance indicators including drying time, internal temperature, humidity levels, and energy utilization were recorded continuously using sensors. Comparative trials with traditional open-sun drying methods were also conducted to benchmark performance. Data were processed through statistical analysis to determine average drying rates, energy efficiency, and product quality retention, including moisture content and sensory evaluation (color, texture, aroma). User feedback on usability and operational challenges was collected through structured questionnaires and focus group discussions. Drying efficiency was evaluated based on reductions in drying time and moisture content. Product quality was assessed through physical and organoleptic tests pre- and post-drying. Energy consumption was analyzed by estimating the equivalent fossil-fuel energy saved. Usability was rated on ease of operation, maintenance needs, and acceptance by MSME operators. The results were analyzed to validate the effectiveness, reliability, and user-friendliness of the developed drying tool for rural food MSME applications.

3. RESULTS AND DISCUSSIONS

Performance Evaluation of the Solar-Powered Drying Device

The developed solar-powered multipurpose drying device was subjected to a series of performance tests under natural rural environmental conditions. The prototype was assessed based on drying time, internal temperature regulation, humidity control, and energy efficiency. Results showed that the device could consistently maintain internal temperatures ranging between 50°C to 65°C during peak sunlight hours, significantly higher and more stable than ambient temperatures, which averaged around 30°C to 35°C. This temperature range was optimal for drying various food products such as fruits, vegetables, and spices without compromising their nutritional and sensory qualities. Drying time for sample products was reduced by approximately 40-50% compared to traditional open sun drying methods. For instance, mango slices that normally took 36 hours to dry under direct sun achieved the desired moisture content in just 20 hours using the solar dryer. This enhancement is attributed to the controlled environment inside the drying chamber, which minimized product exposure to dust, insects, and moisture fluctuations.

Humidity levels within the drying chamber were effectively lowered by improved airflow facilitated by the solar-powered fans, which circulated warm air uniformly throughout the drying trays. Relative humidity was maintained below 20%, a critical factor in preventing microbial growth and ensuring product safety. Energy efficiency analysis revealed that the solar dryer operated entirely on renewable solar energy without auxiliary power, offering significant savings in operational costs compared to electric or fuel-based dryers. The device's solar collector and ventilation system were optimized for maximum solar radiation absorption and heat retention. This performance aligns with other studies demonstrating solar drying devices' effectiveness, yet the multipurpose design's flexibility sets it apart by accommodating diverse product requirements within a single unit. The results confirm that the device offers a reliable, energy-efficient alternative suitable for rural MSME food producers.

Quality Assessment of Dried Food Products

Maintaining product quality post-drying is crucial for MSMEs aiming to supply both local and extended markets. The study evaluated the dried products' physical, chemical, and sensory attributes to determine the drying tool's impact on quality preservation. Moisture content analysis showed that the device achieved a consistent reduction to below 15%, meeting food safety standards for dried products and significantly lowering spoilage risk. Nutritional analyses indicated minimal loss of key vitamins and antioxidants compared to fresh samples, which contrasts positively with traditional drying where nutrient degradation is higher due to uncontrolled exposure to sunlight and contaminants.

Sensory evaluation, conducted by panels of local consumers and MSME operators, reported better retention of natural color, texture, and aroma in products dried with the solar-powered tool. For example, dried chili peppers retained their vibrant red color and pungency, whereas sun-dried counterparts were often discolored and less flavorful. These findings demonstrate that the drying device effectively balances drying speed with quality retention, an important consideration often overlooked in conventional drying methods. The controlled drying environment minimizes enzymatic and oxidative damage to food components. Comparatively, these results show improvement over other solar drying devices that may lack precise airflow control or multipurpose adaptability, leading to product-specific compromises in quality. The ability to tailor drying conditions for different products enhances overall product quality and market competitiveness.

Study Limitations and Future Directions

While the research produced promising results, several limitations were identified. The prototype's dependence on direct sunlight limits operation during extended cloudy or rainy periods, common in certain rural climates, reducing drying reliability. Integrating auxiliary energy sources such as biomass or battery storage could address this limitation. The study focused on a limited range of food products commonly processed by rural MSMEs; expanding product variety and evaluating long-term storage stability post-drying are needed to generalize findings.

User trials were conducted with a relatively small sample size, and scaling up to larger populations and diverse geographic locations will be necessary to confirm widespread applicability and identify region-specific adaptations. The durability of materials under prolonged outdoor exposure requires further long-term assessment to ensure sustained device functionality. Future research should explore modular design improvements, hybrid power systems, and digital monitoring to enhance efficiency and user experience. Additionally, economic impact assessments over multiple production cycles could quantify the device's contribution to rural MSME income growth.

Compared to commercial solar dryers, the developed device was more affordable and adapted to multipurpose use, whereas many commercial units were single-product focused and required higher capital investment. The local material construction also made the prototype easier to maintain and repair compared to imported or complex systems. Performance metrics such as drying time, energy consumption, and product quality favored the developed tool, demonstrating superior thermal efficiency and user satisfaction. These findings suggest that the new device strikes an effective balance between cost, usability, and performance, filling a niche underserved by existing technologies. However, the prototype currently lacks advanced automation features available in some commercial units, such as temperature sensors linked to automatic controls, which could further optimize drying processes. Future iterations could integrate such features while maintaining affordability.

Discussion

The device effectively leveraged solar energy to provide a controlled drying environment, addressing many of the limitations inherent in traditional open-air sun drying. The results show that the drying tool successfully maintained optimal temperature and humidity levels, which directly contributed to faster drying times and improved food quality. The controlled temperature range of 50°C to 65°C during peak sunlight hours significantly reduced drying duration by up to 50% compared to conventional methods. This accelerated drying reduces the window for microbial contamination and spoilage, thereby enhancing food safety. Additionally, the consistent internal environment prevented uneven drying, which often occurs with traditional drying where food exposure to fluctuating conditions can lead to quality degradation.

User feedback affirmed the device's operational practicality and usability, indicating that rural MSMEs could easily adopt the technology with minimal training. The multipurpose design—capable of drying various food products simultaneously—offered significant advantages by maximizing throughput and flexibility. This contrasts favorably with existing solar dryers that are often designed for single-product use and may require costly modifications to switch product types. The quality analysis further supports the tool's efficacy. Products dried in the device retained better color, texture, and aroma, suggesting that controlled drying mitigates enzymatic browning and nutrient loss often seen in open sun drying. These quality improvements align with the growing consumer demand for high-quality, safe dried foods, potentially allowing MSMEs to access higher-value markets.

When compared to other studies on solar drying technologies, this research stands out due to its emphasis on multipurpose functionality combined with affordability and user-centered design. Many prior designs have focused on performance but lack consideration for diverse product needs or cost constraints typical in rural areas. The use of locally sourced materials enhances the tool's sustainability and ease of maintenance, critical factors for long-term rural adoption. However, the study also identified limitations. The drying tool's dependence on sufficient solar irradiance restricts its effectiveness during extended cloudy or rainy periods, which are common in certain rural climates. This limitation could be mitigated in future designs by incorporating hybrid energy sources or thermal energy storage systems to maintain drying operations during low sunlight conditions.

Moreover, while initial user trials were positive, scaling the technology to different geographic and socio-economic contexts requires further validation. Variations in product types, climate, and user capacity may necessitate adaptive design modifications. Finally, the prototype's durability and material longevity under prolonged exposure to outdoor conditions warrant long-term investigation to ensure sustained performance without significant maintenance costs. In summary, the solar-powered multipurpose drying tool addresses key challenges faced by rural food SMEs by combining efficient drying performance, improved product quality, and user-friendly design. While there remain opportunities for enhancements—particularly in energy resilience and scalability—the research provides a robust foundation for advancing sustainable food processing technologies in rural settings.

4. CONCLUSION

This study successfully developed and evaluated a solar-based multipurpose drying tool specifically designed to support food MSME production in rural areas, demonstrating significant improvements in drying efficiency, product quality, and operational feasibility compared to traditional drying methods. The main findings reveal that the device maintained optimal temperature and humidity control, reducing drying time by nearly 50% while preserving key sensory and nutritional attributes of various food products, thereby enhancing their market value and safety. The research contributes a practical, affordable, and user-centered solution tailored to the unique needs of rural MSMEs, incorporating locally sourced materials to ensure ease of maintenance and sustainability. Importantly, the multipurpose design accommodates simultaneous drying of diverse food types, which increases productivity and flexibility for small-scale producers. The implications of this work extend beyond technical innovation, offering rural communities an eco-friendly and cost-effective alternative that can improve income generation, reduce post-harvest losses, and promote sustainable food processing practices. However, the study acknowledges limitations, including the device's dependence on adequate solar irradiance, which restricts performance during cloudy or rainy periods, and the need for further testing across diverse climatic conditions and product varieties to ensure broader applicability. Future research should focus on integrating hybrid energy systems or thermal storage to enhance reliability, exploring modular enhancements for scalability, and conducting long-term durability assessments to optimize material selection and device lifespan. Overall, this manuscript advances knowledge by addressing critical gaps in rural food drying technologies and explicitly answers the research question by providing a viable, multipurpose solar drying solution that empowers rural MSMEs to improve productivity sustainably. The findings lay a solid foundation for continued innovation and adaptation of renewable energy-based food processing tools in developing contexts.

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