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IoT and Solar Powered Storage System for Agricultural Product Quality Enhancement

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Abstract

Postharvest losses remain a critical issue for corn farmers in Sumenep Regency, particularly in Lenteng Timur Village, where traditional storage methods fail to maintain product quality. This study aimed to design and develop an Internet of Things (IoT)-based agricultural storage system powered by renewable energy to enhance product quality, extend shelf life, and reduce farmer losses. The research employed a Research and Development (R&D) approach adapted from the Borg and Gall model, limited to six stages: problem identification, planning, prototype development, preliminary testing, revision, and main field testing. The system integrates DHT22 and MQ-135 sensors with an ESP32 microcontroller and a 200–300 Wp solar photovoltaic system. Field trials demonstrated that the IoT monitoring application provided real-time temperature, humidity, and gas concentration data with <2% deviation. The solar energy system generated 0.8–1.0 kWh/day, sufficient for continuous operation. Corn stored for 30 days in the IoT system exhibited 2.8% weight loss and 13–14% moisture content, compared to 7.4% weight loss and 16–18% moisture in traditional storage. User evaluation indicated high acceptance, with 90% of farmers reporting easier monitoring and 80% finding the system easy to use. These results suggest that integrating IoT and renewable energy in storage systems can effectively reduce postharvest losses, maintain crop quality, and promote sustainable agricultural practices. Further refinements are needed to enhance user-friendliness and backup energy capacity for broader implementation.

Keywords

Agricultural Products, Internet of Things, Postharvest, Renewable Energy, Storage Systems.

1. Introduction

Postharvest losses remain a critical challenge in the agricultural sector, especially in developing countries like Indonesia. The Food and Agriculture Organization (FAO) reports that food losses from harvest to storage and transportation in Indonesia reach 17–30% annually, particularly for staple commodities such as rice and corn (Fabi & English, 2019). Similarly, Nath et al. (2020) note that global cereal losses amount to approximately 19% of total production due to quality and quantity degradation during storage. These figures indicate that improving food security depends not only on increasing on-farm productivity but also on effective postharvest management, particularly in the storage phase.

Sumenep Regency in East Java is one of Indonesia's key corn production centers. Data from the One Data Center of Sumenep Regency (2022) show that corn production increased from 361,737 tons in 2020 to 378,091 tons in 2021, highlighting its potential as a regional food hub. Lenteng Timur Village, the focus of this research, has a strong agricultural tradition and strategic proximity to the district government centre, making it an ideal pilot project site for storage innovation. However, the region faces a hot-humid climate with an average annual temperature of 25–33°C. Such environmental conditions accelerate corn kernel respiration, stimulate mould growth, and heighten the risk of aflatoxin production, which threatens both food quality and human health (Moses et al., 2015; Molnár et al., 2023).

Corn is highly susceptible to postharvest quality deterioration, with temperature and relative humidity being the most critical factors (Molnár et al., 2023). Prolonged exposure to high temperatures ($\geq 30^{\circ}\text{C}$) and fluctuating humidity promotes fungal growth and aflatoxin contamination, risks that are exacerbated by climate change (Moses et al., 2015). Although pre-drying and controlled storage can reduce damage, their effectiveness is limited without continuous monitoring (Mohanraj et al., 2016; Cambaza et al., 2018; Mutungi et al., 2019; Viviane et al., 2023; Asare et al., 2023). Traditional storage methods in rural Indonesia often cannot maintain optimal temperature or humidity, resulting in reduced shelf life, declining crop quality, and economic losses (Kumar & Kalita, 2017). Digital technologies, particularly the Internet of Things (IoT), now offer solutions by enabling real-time monitoring of temperature, humidity, and air quality (Wolfert et al., 2017; Kamilaris et al., 2017; De Alwis et al., 2022; Patil et al., 2023), while embedded sensors and communication systems support automated control and early warning mechanisms to minimize spoilage and improve storage efficiency (Li & Wang, 2021; Esposito et al., 2023).

Another major obstacle in rural areas, including Lenteng Timur, is limited access to stable electricity, which hinders the adoption of active storage technologies. Renewable energy, particularly photovoltaic systems, has been widely explored as a sustainable solution. PV systems equipped with battery storage can provide a reliable energy source to operate cooling and monitoring devices in off-grid or unreliable-grid areas (Kodali et al., 2020; Talpur et al., 2021; Shaik et al., 2023; Hasan et al., 2023; Tomar & Pradhan, 2024). Empirical studies demonstrate that solar-powered systems effectively reduce agricultural yield losses in rural communities, although challenges such as initial investment, maintenance, and user training remain (Amjad et al., 2018; Rutta, 2022). Nonetheless, the long-term cost efficiency and accessibility of solar energy make it a viable option for agricultural applications (Soto et al., 2022; Izuka et al., 2023; Sharma et al., 2024). In the context of postharvest storage, renewable energy ensures continuous operation of IoT-based devices, supporting both environmental sustainability and rural food security (Natarajan, 2023; Husnah & Ichwan, 2023).

Integrating IoT and renewable energy technologies offers a promising approach to overcoming multiple challenges simultaneously: ensuring reliable power,

enabling precise environmental control, and reducing dependence on fossil fuels. Several studies confirm that such combined systems enhance storage performance and extend crop shelf life (Bouali et al., 2021; Wanto, 2022). To develop community-oriented technological solutions, structured frameworks such as the Research and Development (R&D) model by Borg and Gall are highly relevant (Gall et al., 2003). Its iterative stages of design, development, testing, and refinement allow innovations to be adapted to the needs of local farmers, ensuring practical usability and adoption potential.

Based on the above considerations, two key gaps highlight the need for this research. First, corn quality deterioration in Sumenep remains high due to the hot-humid climate and inadequate storage facilities. Second, the limited electricity supply in rural areas prevents the continuous operation of active storage systems. Despite existing studies on IoT-based monitoring (Wolfert et al., 2017; Kamilaris et al., 2017; Patil et al., 2023) and solar-powered storage (Kodali et al., 2020; Talpur et al., 2021; Sharma et al., 2024), an integrated system specifically designed for smallholder farmers in hot-humid regions of Indonesia has not been implemented. This research addresses this gap by designing and constructing an agricultural storage prototype that combines IoT technology and renewable energy in Lenteng Timur Village, Sumenep Regency. The specific objectives are to: (1) monitor storage conditions, including temperature, humidity, and air quality, in real time; (2) control environmental parameters using energy-efficient actuators; (3) utilize solar energy as the primary power source; and (4) evaluate the technical and economic performance of the system on a field scale. By achieving these objectives, the study contributes to reducing postharvest losses, maintaining corn quality, increasing farmer income through improved sales value, and strengthening sustainable food security in rural Indonesia.

2. Methods

This study employed a Research and Development (R&D) approach, applying Borg and Gall's (2003) model up to stage six: research and information gathering, planning, preliminary product development, preliminary field testing, main product revision, and main field testing. Initial observations and structured interviews with 15 corn farmers in Lenteng Timur Village, Sumenep Regency, identified key challenges, including high storage temperatures (30–34°C), relative humidity (70–80%), and postharvest losses due to pest damage, fungal growth, and weight loss. Based on these findings, the system was designed with DHT22 sensors ($\pm 0.5^\circ\text{C}$, $\pm 2\%$ RH) for temperature and humidity, MQ-135 gas sensors for ammonia and ethylene detection, an ESP32 microcontroller with Wi-Fi connectivity, and a photovoltaic-battery system (200–300 Wp, 100 Ah). Threshold values were set at 25–30°C, 50–60% RH, and gas concentration limits for early spoilage detection.

A vertical silo prototype (200 kg capacity) integrating sensors, actuators (DC fan and ventilation), ESP32 microcontroller, and PV-battery system was developed. Preliminary field testing was conducted under controlled conditions for seven days with measurements every 10 minutes to assess sensor accuracy, data transmission stability, energy consumption, and actuator responsiveness. Calibration against standard instruments yielded deviations of $\pm 0.4^\circ\text{C}$ (temperature), $\pm 1.8\%$ RH (humidity), and ± 2 ppm (gas), confirming reproducibility over three consecutive days. Based on the results, the prototype was revised by adding automatic fan relays and reinforcing battery connections to maintain stable environmental conditions and a continuous energy supply.

The main field testing was carried out for 30 days in Lenteng Timur Village, monitoring environmental parameters, energy performance, actuator efficiency, and corn quality before and after storage. Data were transmitted to a web-based IoT application accessible via smartphones, with alarms triggered when critical

thresholds were exceeded. Quantitative analysis compared storage effectiveness against traditional methods, while qualitative feedback from farmers assessed usability, practicality, and sustainability. This methodology validated a prototype capable of real-time environmental monitoring, efficient renewable energy operation, reduction of postharvest losses, and support for sustainable local food security in Sumenep Regency.

Data collection was carried out during the field testing and included environmental parameters (temperature, relative humidity, and gas concentration), system performance indicators (energy consumption, battery performance, and actuator efficiency), and corn quality indicators before and after storage. The data were analyzed both quantitatively and qualitatively. Quantitative analysis focused on comparing the effectiveness of the storage conditions in maintaining corn quality and reducing losses, while qualitative analysis involved gathering feedback from farmers regarding the usability, practicality, and sustainability of the system. Through this method, the study aims to produce a validated prototype capable of monitoring and controlling storage conditions in real time, operating efficiently with renewable energy, reducing post-harvest losses, and supporting sustainable local food security in Sumenep Regency.

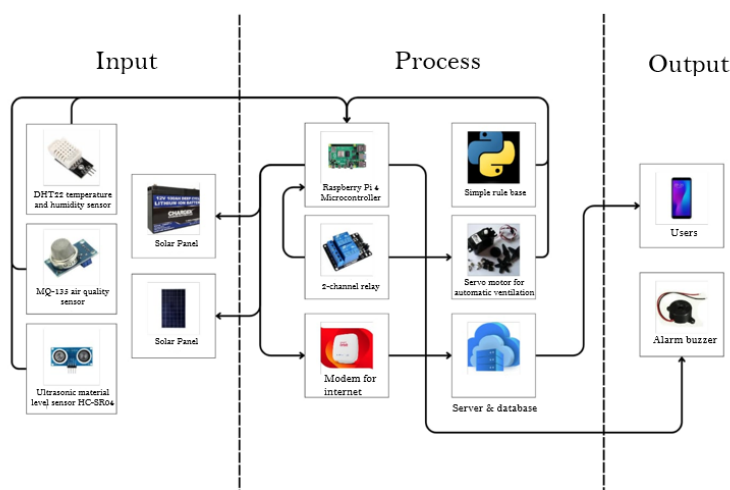


Figure 1. System block diagram of the agricultural product storage system

The block diagram of the agricultural product storage system is shown in Figure 1. The system consists of three main parts: input, process, and output. At the input stage, sensors such as DHT11, MQ-135, and ultrasonic sensors collect environmental data, supported by solar panels as the energy source. In the process stage, data is managed by a Raspberry Pi, processed with Python, and transmitted via a modem to a server and database. Finally, at the output stage, information is delivered to users through mobile devices, and an alarm buzzer provides warnings when critical limits are exceeded.

3. Results

This research resulted in the design and implementation of an Internet of Things (IoT)-based agricultural storage system integrated with renewable energy. The research process was conducted in Lenteng Timur Village, Lenteng District, Sumenep Regency, using a Research and Development (R&D) approach adapted from the Borg and Gall model and limited to six stages: (1) research and information collecting, (2) planning, (3) development of preliminary form of product, (4) preliminary field testing, (5) main product revision, dan (6) main field testing.

Observations indicate that most farmers in Lenteng Timur Village still use traditional storage methods, such as simple barns without temperature and humidity control systems. Storage spaces are generally semi-permanent structures with open ventilation, making them vulnerable to temperature fluctuations, high humidity, and pest attacks.

Observations during the previous harvest season showed that storage temperatures were recorded at around 30–34°C with a relative humidity of 70–80%. This condition accelerates the deterioration of corn quality, including color, texture, and nutritional content. Furthermore, humidity fluctuations contribute to the emergence of *Aspergillus* sp., a fungus that can produce aflatoxin, which is harmful to health. Interviews with 15 local corn farmers were also conducted, and the results revealed that the average postharvest loss ranged from 18–25% of the total harvest within a storage period of approximately 30 days. These losses include physical damage to corn kernels due to pest attacks (10–12%), fungal growth and kernel discoloration due to high humidity (5–8%), and natural weight loss due to kernel respiration (6–8%). These findings align with FAO data in 2019, which reports that postharvest losses in Indonesia for cereal commodities can reach 17–30%. Most farmers expressed the need for storage systems that can maintain corn quality for longer, are easy to operate, and are energy efficient.

The system design stage is a crucial phase in developing a prototype for agricultural storage based on the Internet of Things (IoT) and renewable energy. The design was carried out by considering the needs of users (farmers), the environmental conditions of the research location, and the availability of alternative energy sources. The needs analysis showed that farmers in Lenteng Timur Village face constraints in the form of limited storage facilities that are unable to maintain stable temperature and humidity, resulting in a rapid decline in crop quality, particularly corn.

Based on Figure 2, the prototype agricultural storage system was successfully developed using an ESP32 microcontroller as the control unit, which is equipped with a built-in Wi-Fi module to enable remote monitoring. The system integrates several sensors to measure storage conditions. The DHT22 sensor was used to record temperature and humidity with an accuracy of $\pm 0.5^{\circ}\text{C}$ and $\pm 2\%$ RH, while the MQ-135 sensor functioned to detect ammonia and ethylene gas levels as early indicators of spoilage or fermentation of agricultural products. Data collected from these sensors was processed by the ESP32 microcontroller and transmitted to a web-based application in real time, allowing users to continuously monitor and analyze the storage environment.

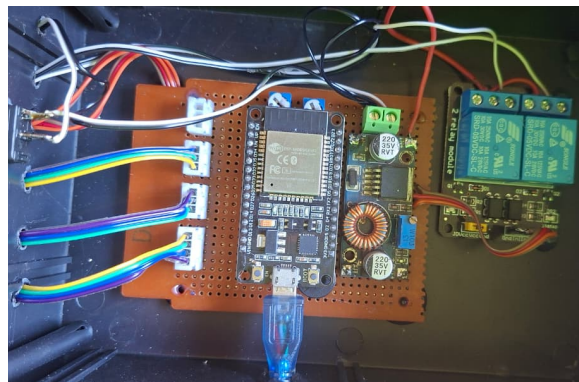


Figure 2. Agricultural product storage system sensor assembly

All sensor data is sent in real time to a web-based server that can be accessed via mobile devices. The application interface is designed simply, featuring graphical

displays of temperature, humidity, gas content, volume, and voltage, making it easy for farmers to understand storage conditions.

The storage system is designed to be energy-sufficient by utilizing 200W solar panels. The generated energy is stored in a 100 Ah lithium-ion battery to ensure continuous 24-hour operation. Energy requirements are calculated based on the power consumption of the sensors, microcontroller, DC fan, and communication module, which totals approximately 120 Wh per day. With this capacity, the solar panels can provide sufficient energy even in cloudy weather conditions.

In this research, a prototype agricultural storage system based on IoT and renewable energy was designed, considering technical functionality, storage capacity, product safety, and energy efficiency.

Based on Figure 3 the agricultural storage prototype was constructed in the form of a vertical silo with an effective capacity of approximately 200 kg of dry corn kernels. The main material was a cylindrical iron plate coated with anti-rust paint to enhance environmental durability. The silo was supported by a steel frame with an angled profile approximately 1.8 meters high, allowing for a space at the bottom for an outlet.



Figure 3. Prototype of an agricultural product storage system

The bottom of the silo was shaped like a conical hopper, facilitating the flow of grain by gravity to the outlet valve. The valve was equipped with a manual control wheel so farmers could adjust the outlet volume as needed. The main door at the top was designed with a tight seal to prevent the entry of moisture and insects.

Prototype validation was conducted through testing the storage system with experts from the fields of agriculture, engineering, and renewable energy, as well as direct input from farmer groups in Lenteng Timur Village, Lenteng District, Sumenep Regency. The validation results showed that the system design met

farmers' needs, particularly the high level of crop damage caused by uncontrolled traditional storage.

Based on the validation results, the prototype was refined by adding a low-power DC fan connected to an automatic relay. The fan is set to activate when the storage temperature exceeds 30°C, thus maintaining temperature stability within the optimal range (25–30°C). The sixth stage of this research was to test the revised product to more comprehensively assess the performance of the Internet of Things (IoT) and renewable energy-based agricultural storage system. The trial was conducted in Lenteng Timur Village, Lenteng District, Sumenep Regency, involving local farmer groups as the primary users.

Test results showed in Figure 4 that the IoT-based monitoring system functioned optimally in monitoring storage environmental conditions. The main parameters monitored included temperature, relative humidity, ammonia gas levels, volume, and voltage. Sensor data was transmitted in real time to a smartphone-based application accessible to farmers. The accuracy of the sensor readings compared to standard measuring instruments showed an average deviation of <2%, thus concluding that the sensor device is suitable for use on an operational scale.

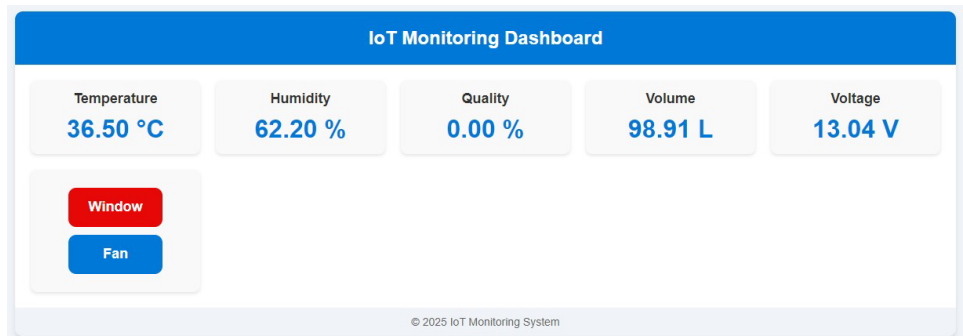


Figure 4. IoT monitoring dashboard

The energy source used in the system is a 300 Wp solar panel connected to a storage battery. During the trial period, the average energy generated reached 0.8–1.0 kWh per day with an 85% utilization rate. These results are sufficient to support the electricity needs of the IoT system and ventilation fans without using conventional energy sources. Therefore, this system can be categorized as energy-efficient and environmentally friendly.

Quality testing of stored corn showed that the weight loss rate during the 30-day storage period was only 2.8%, lower than the 7.4% achieved using traditional storage methods. Furthermore, the corn moisture content was maintained at 13–14%, in line with safe storage standards to prevent mold growth. This demonstrates that the storage system can extend the shelf life of agricultural produce while maintaining product quality. The following is Figures 5 and 6, a comparison of weight loss during storage using an IoT-based renewable energy storage system with traditional storage.

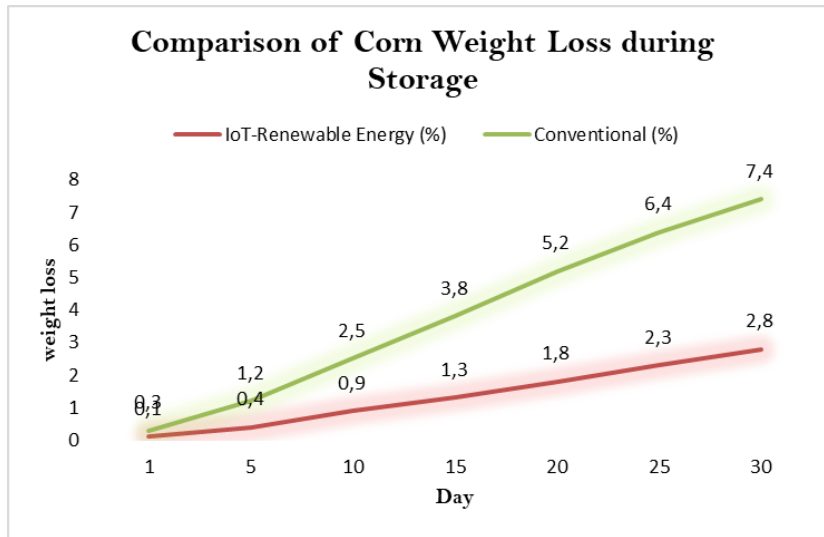


Figure 5. Comparison of corn weight loss during storage

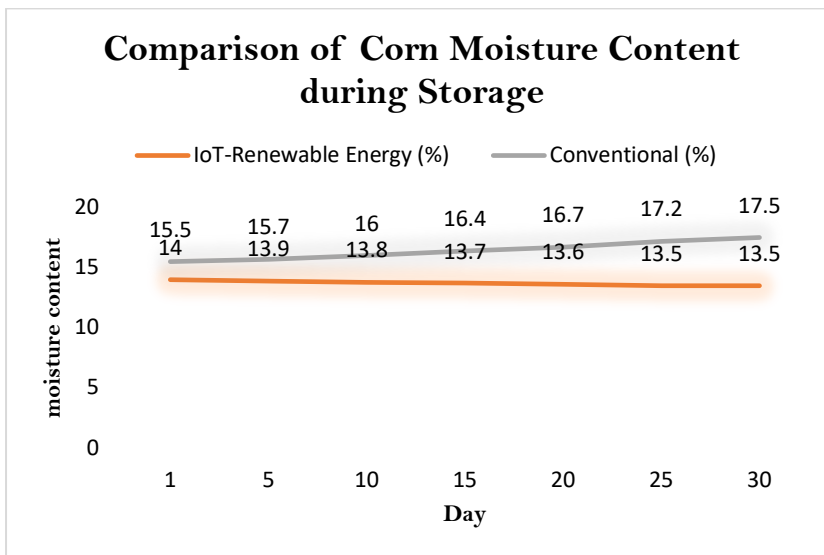


Figure 6. Comparison of corn moisture content during storage

Table 1. Comparison between IoT–Renewable Energy Storage and Traditional Storage

Parameter	IoT System– Renewable Energy	Traditional Storage
Effective storage period	≥ 30 days	15–20 days
Weight loss	2.8 %	7.4 %
Corn moisture content	13–14 %	16–18 %
Potential for fungal attack	Low	High
Electricity consumption	100% solar energy	Dependent on PLN/Non-IoT
Access Condition Information	Real-time via app	Manual/visual

To provide a quantitative overview, the system test results are compared with traditional storage methods, as shown in Table 1. Interviews with 10 farmer respondents showed that 90% of farmers found the system helpful because it allows them to monitor storage conditions without having to perform manual checks.

Eighty percent of respondents stated that the system was easy to use, while 20% still experienced technical difficulties understanding the application. These challenges indicate the need for additional training before the system is widely implemented.

The main field testing demonstrated that the IoT-based storage system and renewable energy are effective in reducing post-harvest yield losses, increasing energy efficiency, and simplifying the crop management process for farmers. However, further evaluation is needed to improve backup energy capacity and improve the application's user interface to make it more user-friendly.

4. Conclusion

This research successfully designed and implemented an Internet of Things (IoT)-based agricultural storage system integrated with renewable energy to improve the quality and durability of agricultural products, particularly corn, in Lenteng Timur Village, Sumenep Regency. The developed system is capable of monitoring storage conditions in real time, maintaining stable temperature and humidity, and controlling potential damage from fungi and pests.

Test results showed that the use of a 300 Wp solar panel with a storage battery can provide sufficient energy to operate the system continuously for 24 hours. The corn weight loss rate during 30 days of storage was only 2.8%, significantly lower than the 7.4% achieved with traditional storage. Furthermore, the moisture content was maintained at 13–14%, ensuring the corn quality met safe storage standards. Interviews with farmers indicated high usability and satisfaction, although some users require additional training to fully operate the system.

This system is effective in reducing post-harvest yield losses, increasing energy efficiency through renewable energy, and simplifying monitoring for farmers via an IoT-based application. Beyond technical performance, the study demonstrates potential community and policy impacts: adoption of such systems can strengthen rural food security, reduce economic losses for smallholder farmers, and encourage sustainable energy practices in agricultural sectors.

The study has limitations, including the relatively small storage capacity, localized field testing in a single village, and limited long-term evaluation under varying weather conditions. To further validate and scale the system, future research should explore larger-scale implementation, integration of predictive analytics for spoilage detection, refinement of the mobile application interface for user-friendliness, and expansion to different commodities and regions. These steps will ensure broader adaptability, enhance farmer adoption, and inform policy measures promoting renewable energy-supported postharvest technologies in rural Indonesia.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest.

Ethical Approval and Originality Statement

Ethical approval was obtained for this study. The manuscript represents original work and has not been previously published, nor is it under consideration by another journal.

Data Disclosure Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.



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