

## Development and performance evaluation of a Bluetooth-enabled grain inversion machine for efficient grain drying for small and marginal farmers

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### Abstract

Uniform grain drying is essential for reducing post-harvest losses, but repeated manual turning during open-sun drying is labour intensive and often inconsistent. This study evaluated a Bluetooth-operated unmanned grain turning system developed to improve open-sun drying efficiency and grain moisture uniformity while reducing labour and energy demand. Comparative field trials were conducted under similar drying-floor conditions using grain lots with an initial moisture content of 22% (wet basis). The performance of the developed grain inverter model was assessed against traditional, manual turning and static drying. Moisture reduction data showed that the developed system dried grain faster throughout the drying period, reducing moisture from 22% to 12% within 7 h, whereas the traditional method retained 14% moisture after the same period. The average drying rate of the developed model was 1.43% h<sup>-1</sup> higher than the 1.14% h<sup>-1</sup> recorded for the traditional method, confirming enhanced heat and mass transfer due to continuous grain inversion. Total drying time was reduced to 7 h compared with 9 h for manual turning and 10 h for static drying. The developed system also improved drying uniformity, showing very low moisture variation and a nearly uniform layer-wise moisture distribution of 12.2%, 12.0%, and 11.8% in the top, middle and bottom layers respectively, compared with greater gradients in manual turning and static drying. In addition, energy consumption was lower for the developed system (4.5 kWh) than for manual turning (5.5 kWh) and static drying (6.0 kWh). Overall, the Bluetooth-operated unmanned grain turning system demonstrated superior drying efficiency, reduced drying time, better moisture uniformity, and lower energy requirement, indicating strong potential as a practical and economical solution for safer grain drying at farm level.

**Keywords:** Used grain drying, unmanned grain turning system, bluetooth control, drying uniformity, labour-saving mechanization, post-harvest management

### Introduction

#### Grain Production in India

Agriculture remains one of the foundational sectors of the Indian economy, not only as a source of livelihood for a large share of rural households but also as a pillar of national food security. Grain crops occupy a central place in this agricultural landscape because they supply staple calories, feed livestock, and support a broad chain of activities that includes procurement, transport, milling, and trade. In recent years, India has consistently remained among the world's largest grain-producing countries, with annual foodgrain output crossing hundreds of millions of tonnes. Official final estimates show that total food grain production increased from 332.30 million tonnes in 2023–24 to a record 357.73 million tonnes in 2024–25, while rice and wheat production reached 150.18 and 117.95 million tonnes, respectively (PIB, 2025). This scale of production creates both an opportunity and a challenge: while harvest volumes are high, preserving grain quantity and quality after harvest requires equally strong post-harvest systems (Department of Agriculture and Farmers Welfare, 2023; FAO, 2026) [5].

The major grains produced in India include rice, wheat, maize, and millets, each with distinct agro-climatic requirements and market lanes. Rice and wheat dominate the national foods rain basket and are critical to public distribution and household consumption. However, increases in production alone do not guarantee food and income security gains can be undermined if harvested grain is lost, damaged, or downgraded before it reaches storage or

market channels (Department of Agriculture and Farmers Welfare, 2023) [5]. Post-harvest losses in grains remain a serious concern in India and many other developing agricultural economies. These losses occur during threshing, transport, drying, storage, and handling, and they reduce both physical quantity and commercial quality. A large fraction of post-harvest damage is linked to inadequate moisture management in the period immediately after harvest. Grain harvested with elevated moisture cannot be safely stored for long durations because the biological activity of kernels and microorganisms remains high. If drying is delayed or incomplete, the grain mass becomes vulnerable to heating, discoloration, germ damage, insect infestation, and microbial proliferation, all of which reduce shelf life and market value (Kumar and Kalita, 2017; Hodges *et al.*, 2011) [7, 8].

In many farming regions, especially at the small and medium scale, sun drying remains the most common and economical method. Freshly harvested grains are spread in thin layers on open yards, roadsides, tarpaulins, or drying floors and exposed to solar radiation and ambient airflow. Although this method is low-cost and accessible, it often produces uneven moisture removal. Variations in layer thickness, surface temperature, wind movement, cloud cover, and orientation to sunlight cause some grain portions to dry faster than others. As a result, the final batch can contain a mixture of adequately dried and partially wet grains, creating hidden instability during storage. Non-uniform drying is thus a major technical limitation of traditional open-sun systems (Brooker *et al.*, 1992; Kumar and Kalita, 2017) [3, 8].

To moderate this non-uniformity, farmers depend on heavily on repeated manual turning or inversion of the grain layer. Workers use rakes, spades, or wooden tools to disturb and rotate grain at regular intervals so that wetter portions are exposed to sunlight and airflow. While this practice improves uniformity, it demands continuous physical effort, close supervision, and substantial time commitment, particularly for large drying areas. In many areas, seasonal labour shortages and migration trends have further reduced the availability of timely manual work. Consequently, grain turning becomes a bottleneck that can delay drying completion, increase weather exposure risk, and elevate total post-harvest handling costs (Kumar and Kalita, 2017) [8].

These constraints underline the need for mechanized, practical, and affordable interventions tailored to field realities. Large industrial dryers and automated handling systems exist, but their capital and energy requirements make them inaccessible to many smallholders. It needed is an intermediate technological solution simple in design, low in operating complexity, robust under outdoor conditions, and capable of reducing human drudgery while improving moisture uniformity. Mechanized turning can shorten drying cycles, reduce dependence on scarce labour and standardize handling quality across batches. By improving the consistency of moisture reduction, such systems can also strengthen storage safety, reduce quality claims at sale points, and enhance farmer confidence in post-harvest operations. Related recent development studies on battery-powered field machinery, cost economics of newly developed implements, and value-addition products also indicate the broader relevance of practical farm engineering innovations (Praveen *et al.*, 2025; Vinayak *et al.*, 2025a,b) [11, 13, 14].

Against this background, the present study was development of an unmanned grain turning system for uniform grain drying, proposes an unmanned grain turning model that employs three dedicated turning tools to automate the inversion process during sun drying. The conceptual objective is to eliminate repetitive manual turning while ensuring that grain layers are continuously redistributed for more uniform exposure to heat and air. By integrating affordability, operational simplicity, and functional effectiveness, the proposed system aims to offer a scalable solution for farm-level and community-level drying platforms. Ultimately, the development of such an unmanned turning mechanism can contribute to reduced post-harvest losses, better grain quality preservation, and more resilient grain value chains (Kumar and Kalita, 2017) [8].

## Materials and Methods

This section explains the materials and procedures used to develop the bluetooth operated grain turning model.

### 1. Materials Used

The prototype was built using readily available electrical and mechanical components suitable for low-cost agricultural mechanization. A microcontroller board was used as the main control unit to read wireless commands and generate control signals for motor actuation (Arduino, 2026) [1]. The selected board provides digital pins and PWM outputs required for direction and speed control. Wireless communication was established through bluetooth module mounted on the vehicle (Bluetooth SIG, 2023) [2]. The module receives command inputs from a smartphone and

transmits them to the microcontroller through serial communication. A rechargeable battery was used as the power source for the complete system. A mobile application with directional keys was used to connect to the Bluetooth module and remotely operate the vehicle.

For mobility four small DC geared motors were employed one for each wheel. This arrangement provides adequate traction on drying-floor surfaces and allows directional control through differential wheel motion. An H-bridge motor driver module was interfaced between the microcontroller and motors to supply current and enable forward/reverse operation. The mechanical structure consisted of a rectangular chassis/frame fabricated from light weight metal or rigid plate material with mounting provisions for electronics, battery, and tool assembly. Four wheels were fixed to the motor shafts.

Three grain inversion tools were attached at the rear of the vehicle with fixed spacing. These tools were shaped to drag through the top grain layer and reorient kernels during movement. Supporting items included wiring harnesses, terminal connectors, on/off switch, motor mounts, fasteners, spacer plates, and protective brackets used for rigid assembly and routing of electrical lines.

### 2. Development of Model

The model was created in SolidWorks 2022 as a compact platform intended for operation on sun-drying floors (Dassault Systems, 2022) [4]. Figure 1 presents the CAD view of the four wheel vehicle with three rear-mounted grain inversion tools. The main design objective was to integrate propulsion, wireless control, and grain inversion in a single lightweight unit. A rectangular chassis was selected to simplify fabrication and to provide stable support for four-wheel placement. Each corner of the frame carries one DC motor-wheel pair producing a balanced load distribution and stable straight-line travel over loose grain surfaces.

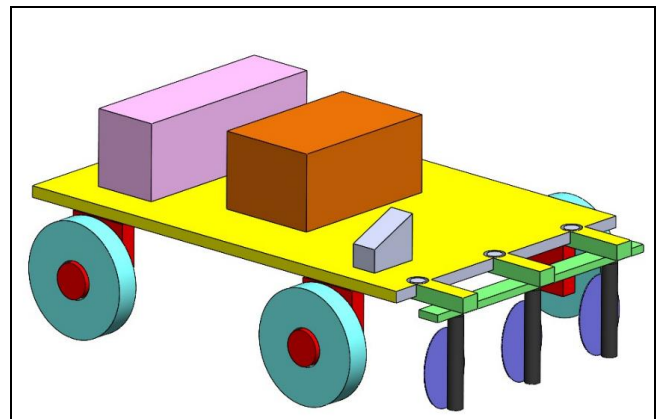


Fig 1: SolidWorks 3D model of the unmanned grain turning vehicle with three rear inversion tools.

The rear side of the chassis carries three inversion tools arranged laterally across the effective working width. During vehicle motion, these tools disturb the upper grain layer and shift grains from one position to another, reducing moisture non-uniformity caused by static drying. Clearances between wheel level and tool tip were defined so that tools contact the grain bed without excessive scraping of the drying floor.

### 3. Bluetooth Control System

The control system uses a phone-to-vehicle Bluetooth link for command transmission. After pairing the mobile

application with the onboard Bluetooth module, the user sends directional commands such as forward, backward, left, and right. These commands are transmitted as coded characters and received by the microcontroller. The microcontroller decodes each command and executes the corresponding motor routine. Output pins drive the motor driver module, which energizes the four DC motors with the required polarity and current. To improve operational safety, the program includes a stop condition when no valid command is received within a defined interval.

#### 4. Working Methodology

The operational sequence of the developed system is as follows:

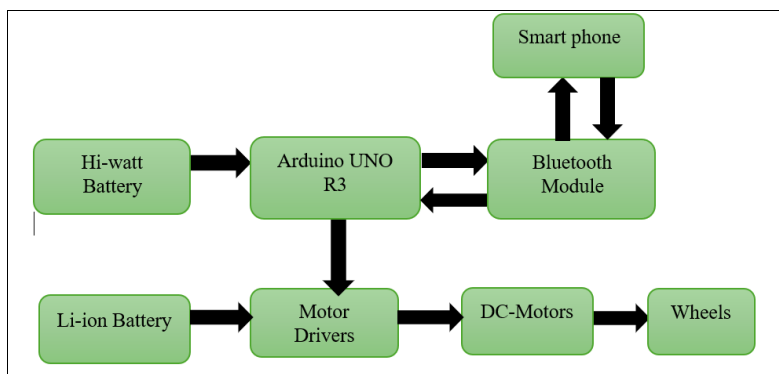
1. The rechargeable battery is charged and connected to the power circuit feeding the microcontroller, Bluetooth module, motor driver, and DC motors.
2. Grain is spread on the drying floor in a thin, approximately uniform layer, and the unmanned vehicle is placed at the boundary of the drying area.
3. The user opens the mobile application, enables

Bluetooth, and pairs the phone with the onboard Bluetooth module.

4. Movement commands are sent from the application according to the required travel path across the grain bed.
5. The microcontroller receives each command and controls the motor driver to rotate the four wheel motors in the desired direction.
6. While moving, the three rear inversion tools drag through the grain layer, turning and mixing grains to expose wetter portions to sun and airflow.
7. Repeated passes with slight overlap are performed until full area coverage is achieved, and turning cycles are repeated at selected time intervals.

This procedure converts manual grain turning into a repeatable mechanized operation with consistent coverage.

#### 5. Working Principle of Bluetooth Operated Grain Inversion Equipment



#### 6. Testing and Evaluation of Bluetooth Operated Grain Inversion Model

Procedure To maintain direct comparability between manual turning and the developed model, performance testing was carried out under the same open-sun drying context used for the final analysis. Both methods were applied on comparable grain lots with similar initial moisture level, layer thick ness, drying-floor condition, and daytime operating window. Observations were recorded from the beginning of drying until completion for each method and then organized for indicator-wise comparison (Brooker *et al.*, 1992; Kumar and Kalita, 2017) [3, 8]. The evaluation procedure included three groups of indicators: 1. Moisture content variation with respective to drying hours 2. Drying rate analysis 3. Drying time comparison 4. Percentage of moisture variation at different methods 5. Energy Consumption Analysis 6. Layer-wise Moisture Distribution

#### Results and Discussion

Comparative field trials were conducted to evaluate the performance of the Bluetooth operated unmanned grain turning system against the traditional manual turning

method under open-sun drying conditions. For consistency, both methods were tested with comparable grain lots, similar initial moisture levels, and equivalent drying-floor conditions during daytime operation. The analysis was limited to table-based results and discussion, with emphasis on moisture reduction, drying time, layer-wise uniformity, labour demand, turning frequency, and turning coverage area (Brooker *et al.*, 1992; Kumar and Kalita, 2017) [3, 8].

##### 1. Moisture content variation

The variation of moisture content with drying time for both the developed grain inverter model and the traditional drying method is presented in Fig. 3.1. and Table 3.1. The initial moisture content of the grains was 22% (wet basis) for both methods, ensuring a uniform basis for comparison. As drying progressed, the moisture content decreased continuously in both cases; however, the developed grain inverter model exhibited a significantly faster reduction. After 1 hour of drying, the moisture content decreased to 20% in the grain inverter model, whereas it remained higher at 21% in the traditional method. At 2 hours, the moisture content further reduced to 18.5% in the developed system compared to 19.5% in the traditional method.

**Table 1:** Moisture reduction in the grain inverter machine compared to traditional method

Time (h)	Grain Inverter model (%)	Traditional method (%)
0	22	22
1	20	21
2	18.5	19.5

3	17.3	18
4	16.2	16.8
5	15.2	15.5
6	13.8	14.5
7	12	14

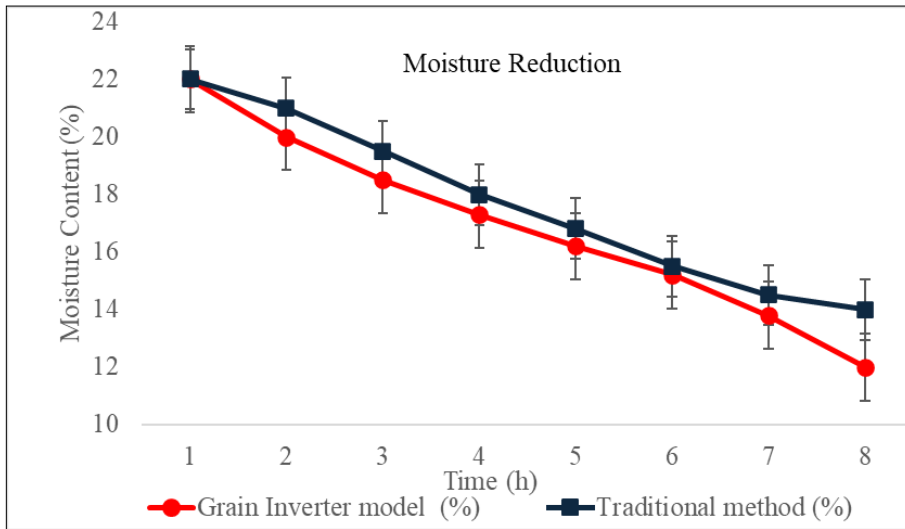


Fig 1: Moisture reduction comparison for developed model and traditional method

This trend continued throughout the drying period. At 4 hours, the developed system reached 16.2%, while the traditional method recorded 16.8%. At 6 hours, the moisture content in the grain inverter model dropped to 13.8%, whereas the traditional method showed 14.5%. By the end of the drying period (7 hours), the developed model achieved a final moisture content of 12%, which falls within the safe storage range. In contrast, the traditional method retained a higher moisture content of 14%.

The faster moisture reduction in the developed system can be attributed to continuous grain inversion, which enhances exposure to sunlight and airflow, thereby improving heat and mass transfer. The graphical trend (Fig. 4.1) clearly shows a steeper decline in moisture content for the grain inverter model, indicating higher drying efficiency.

## 2. Drying Rate Analysis

The drying rate comparison between the grain inverter model and the traditional method is shown in Fig. 4.2. The drying rate of the developed system was found to be 1.43% per hour, while the traditional method exhibited a lower drying rate of 1.14% per hour. Table 3.2 and Fig.3.2. represents the drying rate analysis.

Table 2: Drying duration for grain inverter machine and traditional method

Method	Drying Rate (% per hour)
Grain Inverter	1.43
Traditional Method	1.14

The higher drying rate in the developed system is due to continuous grain inversion, which improves heat and mass transfer. The inversion mechanism ensures uniform exposure of all grain particles to drying conditions, thereby accelerating moisture removal. The Fig 4.2 represents the drying duration for grain inverter model and traditional method. The graphical representation clearly indicates that

the developed system is more efficient in removing moisture per unit time compared to the traditional method.

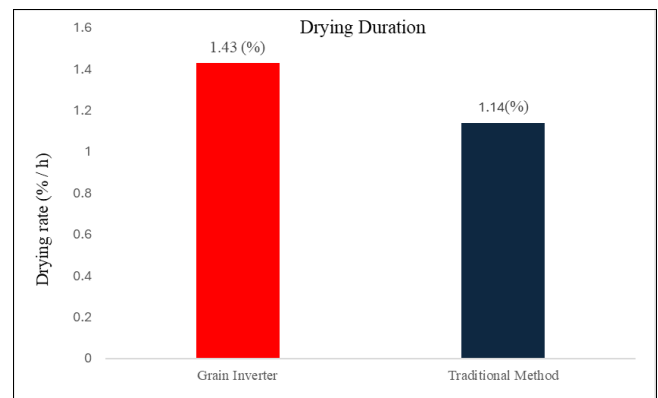


Fig 2: Drying duration for grain inverter machine and traditional method

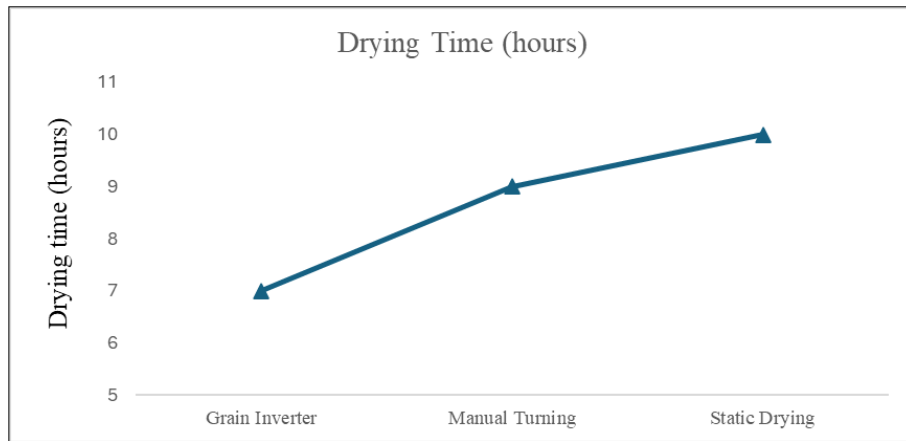
## 3. Drying Time Comparison

The total drying time required for different methods is presented in Fig. 3.3. and Table 3.3. The grain inverter model required only 7 hours to complete the drying process, whereas manual turning required 9 hours and static drying required 10 hours.

Table 3: Drying time comparison

Method	Drying Time (hours)
Grain Inverter	7
Manual Turning	9
Static Drying	10

This indicates a significant reduction in drying time of about 2 to 3 hours when using the developed system. The reduction in drying time improves operational efficiency and reduces the risk of grain spoilage due to environmental conditions.



**Fig 3:** Drying time comparison for grain inverter, manual turning and static drying

The graph clearly shows that the developed system is the fastest among all methods, demonstrating its superior performance.

#### 4. Moisture variation

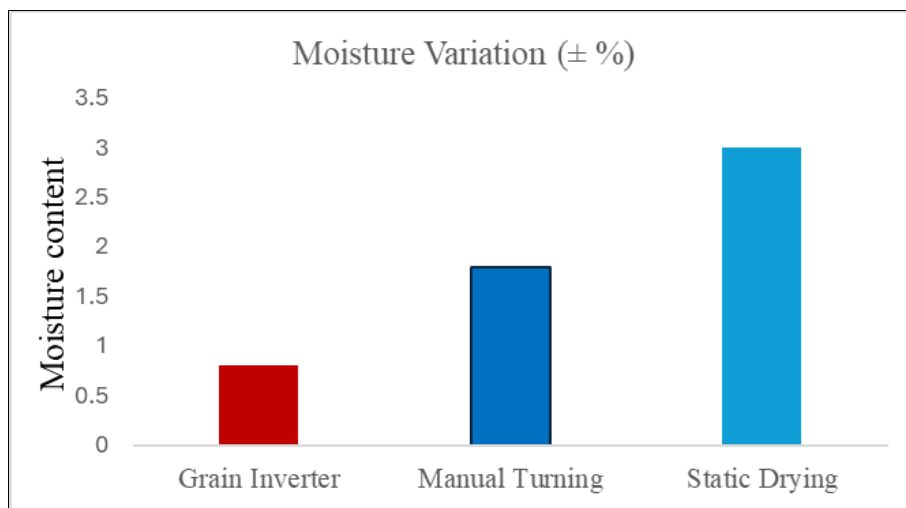
Moisture variation within the grain mass is a critical parameter that indicates drying uniformity. The moisture variation for different methods is presented in Fig. 4.4. The developed grain inverter model exhibited a very low moisture variation of  $\pm 0.8\%$ , whereas manual turning showed  $\pm 1.8\%$ , and static drying showed the highest variation of  $\pm 3\%$ .

**Table 4:** Moisture variation for different methods

Method	Moisture Variation ( $\pm \%$ )
Grain Inverter	0.8
Manual Turning	1.8
Static Drying	3

Further detailed analysis indicates even lower variation values of 0.4% for the grain inverter, compared to 2.2% for manual turning and 5.5% for static drying. These results confirm that the developed system provides highly uniform drying. The reduction in moisture variation is due to

continuous inversion, which prevents moisture accumulation in specific regions and ensures uniform exposure of grains. The graphical representation Fig 3.4 and Table 3.4. clearly highlights the superior uniformity achieved by the developed model.



**Fig 4:** Moisture variation for different drying methods

#### 5. Energy Consumption Analysis

The energy consumption for different drying methods is presented in Fig. 3.5. and Table 3.5. The developed grain inverter model consumed 4.5 kWh, whereas manual turning required 5.5 kWh, and static drying consumed 6 kWh.

The lower energy consumption of the developed system is attributed to efficient operation and reduced drying time. Faster drying minimizes energy usage, making the system more economical and environmentally sustainable.

**Table 5:** Energy consumption for different methods

Method	Energy (kWh)
Grain Inverter	4.5

Manual Turning	5.5
Static Drying	6

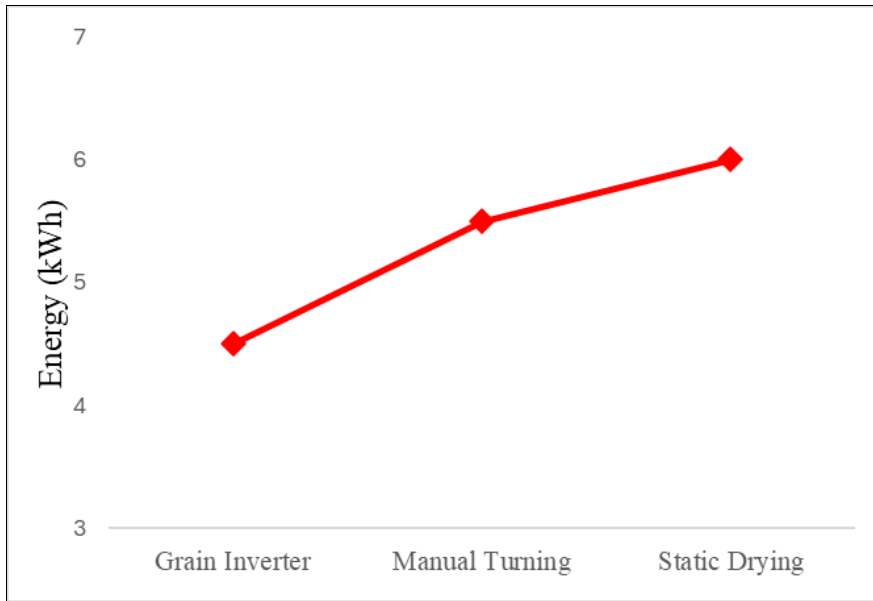


Fig 5: Energy requirement for different methods

### 6. Layer-wise Moisture Distribution

The layer-wise moisture distribution after drying is shown in Fig. 3.6. and Table.3.6. In static drying, significant

variation was observed, with moisture content of 10.5% in the top layer, 13.8% in the middle layer, and 16% in the bottom layer, indicating poor uniformity.

Table 6: Layer wise total moisture distribution

Layer	Static Drying (%)	Manual Turning (%)	Grain Inverter (%)
Top	10.5	11.3	12.2
Middle	13.8	12.6	12
Bottom	16	13.5	11.8

In manual turning, the moisture distribution improved slightly, with values of 11.3%, 12.6%, and 13.5% for top, middle, and bottom layers, respectively. However, the

developed grain inverter model exhibited highly uniform moisture distribution, with values of 12.2% (top), 12% (middle), and 11.8% (bottom).

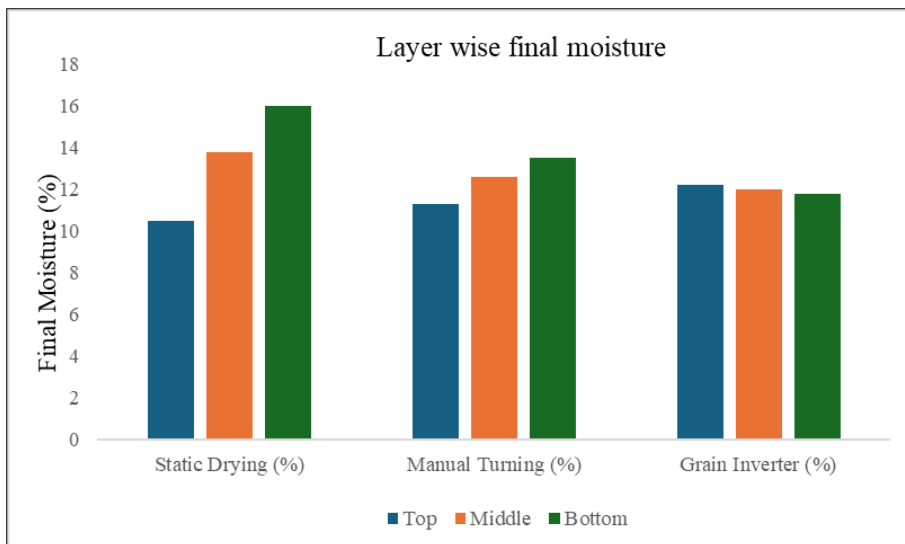


Fig 6: Layer wise final moisture distribution

The reduced variation across layers demonstrates that the inversion mechanism effectively eliminates moisture gradients. The graphical representation (Fig. 3.6) clearly shows that the developed system achieves superior uniformity compared to other methods.

### Conclusion

This study concludes that the developed Bluetooth-operated unmanned grain turning system is more effective than traditional/manual and static drying methods for open-sun grain drying. It reduced grain moisture from 22% to 12%

within 7 h, achieved a higher drying rate (1.43% h<sup>-1</sup>), lowered energy use to 4.5 kWh, and produced more uniform drying across grain layers. The system also shortened total drying time by 2–3 h compared with manual turning and static drying, thereby reducing labour burden and the risk of spoilage. Hence, the developed model offers a practical, efficient, and economical approach for improving farm-level grain drying operations.

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