Maize Grain Forced-Convection Mechanical Drying Process Optimization: A Case of Concession Depot of Company X in Zimbabwe

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Grain drying is a process that succeeds harvesting and is performed to sustainably maintain the properties of grain during the storage period. Elevated moisture content in grains shortens their shelf life, as it promotes bacterial growth. In this present research, the maize grain mechanical drying process parameters; drying air temperature (30 ºC, 60 ºC, and 110 ºC), airflow rate (1.2 m/s, 1.5 m/s and 1.8 m/s), and drying time (30 min, 120 min, and 180 min); were investigated and optimized as regards their effect on the on the dried grain quality and moisture reduction process to minimize the desiccating energy consumption. A full factorial design of experiment was planned, and optimization was carried out utilizing statistical tools, including analysis of variance and the main effects plot signal-to-noise ratio. Results revealed that the evaluated dehydration process parameters, air temperature, and air flow rate, significantly influenced the drying dynamics, whilst the time parameter displayed minimal impact on the process. The optimum drying process parameters were established to be 30 ºC drying temperature, 1.5 m/s airflow rate, and 120 min drying process run time. The percentage error margin between the predicted and confirmation experimental run results at the optimum parameter setting condition was less than 15%.

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INTRODUCTION

Maize constitutes one of the principally vital cereals in the world. Grain drying, an operation process which is carried out in between harvest and storage, is one of the most intensive energy consuming activities during post harvesting maize grain processing (Bhattacharjee *et al*. 2024). Basic grain mechanical drying involves the removal of a large amount of moisture from the grains, by mechanized energy applications, after field harvesting in an effort to avoid spoilage and retain the quality (Jimoh *et al*. 2023). This is done just prior to packing or loading onto the long-term storage facility. In other words, it is the mechanically assisted thermal energy application process intent on agitating the movement of moisture, from the grain kernels to the air, when the vapor pressure within the kernel is higher than that of the air surrounding the kernels. Conventionally, hot air draught is used as an external agent to dehydrate the grains where the temperature, relative humidity, and rate of airflow determine the drying rate of grain. Low moisture content in the grain, on harvesting, is an essential requirement for mechanized production of grain maize products (Müller *et al*. 2022). Furthermore, moisture content is a significant factor in the grain yield quality for upward processing operations and storage of the maize after harvesting. Subtraction of, or diminution of grain moistness facilitates post-harvest processing and forestalls microbiological depreciation. For this reason, drying can improve preservation of the nutritional benefit preservation as well as the commercial worth of the grain (Jimoh *et al*. 2023). In an effort to promote commercialization, subsequent to harvesting, the grains require storage, and its quality preserved all the way through the process duration (Su *et al*. 2022). Therefore, evaluation of grain moisture content lowering technology performance is vital for process optimization. In Zimbabwe, farmers sell their grain to company X during each harvesting season. Grain deliveries occur during the immediate post rain season, soon after harvesting is completed. That is the period during which the atmospheric environmental humidity is significantly decreased during the low moisture dry season. The maize is graded, and its moisture content is determined before it is stored in silos. Those maize grains having a moisture content of 12.5% and below are sent to the storage silos, while the one that is above 12.5% is first sent to the mechanical grain dryers for moisture reduction. The goal of the grain dehydration practice is to produce homogeneous moisture content in the grain of diverse humidity content and dissimilar air conditioning. Maize drying is utilized in preparing maize grain for extended duration length in storage. The course of action is accomplished by transferring the maize grain into the drying chamber and running the dryer for a determinate time duration in order to realize the desirable level of moisture content, which is 12.5% in terms of the grain storage standard in Zimbabwe (Tatum 2024). The different factors affecting the drying process are discussed below.

The advancement of agricultural sciences and technology application, in maize production, has resulted in significant increases in the harvesting of the maize cereal in Zimbabwe in the recent past seasons. In the recently preceding few years, the production of maize has steadily increased, from the farming community in Zimbabwe. The rapid increase in production is because of the increased utilization of hybrid seed, by the farmers, employment of more advanced agronomical practices by the farming community, as well as the apparent elevated market requirement from the feedstock processing industry. This development had inherently given impetus to the application and operation of mechanized maize grain moisture content reduction, artificial drying, at the company X main storage station at concession. Invariably, grain drying is considered as one energy-intensive operation (Jimoh *et al*. 2023), of grain processing, in preparation for long term storage. As such, the drying facility need to be operated efficiently with operating conditions optimally set.

The Concession depot, of company X, run two mobile mechanical grain dryers and 24 storage silos. Electrical energy is used to power the auger screw which provides mechanism of transferring grain from the inlet hopper to the dryer chamber. Hot air is blown into the drying chamber by an electrically powered fan. Heat energy is released by the diesel burners, to raise the air temperature for the drying process. The drying of maize is carried out in batches and at the end of each batch, after which the maize is conveyed to another chamber and allowed to cool naturally to ambient temperature. The capacity of the dryer is on average 15 tonnes per hour against the silo plant intake of 850,000 tonnes, at the depot. Grain processing acceptance record, at the plant, show that 40% of the maize delivered to the plant have moisture content exceeding the recommended value of 12.5%. Hence the grain drying process is in a bottleneck operation of the of the placement of the grain under safe storage.

The performance capacity of the dryer is explained in terms of the drying time per batch and the cooling time. The plant uses natural cooling, and this has a bearing of further limiting the capacity of the dryer. The duration of drying each batch depends on several factors such as air velocity, relative humidity, cooling air temperature, initial moisture content, and mass of product per unit exposed area (Manandhar *et al*. 2018; Pandey and Bolia 2023). Other factors for evaluating a dryer's effectiveness include drying efficiency, uniformity of drying, and end-product quality (degree of cracking and discoloration of grain), as well as total drying time (Adefemi and Ilesanmi 2018; Etım *et al*. 2023). Good functioning of a drying plant point towards appropriate quality outcome acreages of desiccated product, such as minimal and homogenous grain moisture content, marginal quantity of fragmented or broken grain, little mould amount and elevated nutritious worth (Dębowski *et al*. 2021). High drying plant effectiveness is as well required. An optimization of the process could be utilised to operate on factors that influence the desiccating function physiognomies such that a selection set of parameters level (Etım *et al*. 2023) which yield lowest or highest accomplishment outcome, whichever is desirable is established. According to Chojnacka *et al*. (2021) in concurrence with Omofoyela *et al*. (2017), several factors influence the rate of grain drying during mechanical withering process, *viz*: moistness dispersion rate within the grains; temperature and speed levels of the air flow; grain bed depth on the drying trays; grain permeability; average initial humidity content of the grains being loaded for drying; dehydration method; nature of the grain; the drying vessel shape outline and ambient surrounding air moistness; the grain surface area in exposure to the drying air movement due to the mechanical whooshing force, *inter alia*. Kumar *et al*. (2019) state that the effectiveness of a drying plant is influenced by the forced air convection flow rate and the dehydration temperature. There is a need to optimize the controllable parameters in order to minimize the drying time whilst simultaneously also maintaining the quality of grain. Drying air temperature, airflow rate and drying time impact, on the grain desiccating process, were investigated and optimised in this research.

This study focused on mitigating the long-time established mechanical grain drying process challenge which has become a bottleneck in the operation of the silo storage loading system. This problem is apparent in the records at the Concession depot of Company X. The drying process was also established to be highly energy consumptive, yet it still produces inconsistent gain quality due to the erratic occurrence of the drying challenges. The effectiveness of the drying operation is recurrently below the expected level. Various theories were proffered in explanation of this unsatisfactory performance at the plant. Uneven air flow distribution in the driers was noted to lead to poor drying results due to inadequate drying air in some areas of the dryer and, as a result, uneven grain drying. Another reason cited was improperly sized drying fans (too small). This resulted in insufficient air flow (and velocity). On the other hand, oversized fans resulted in excessive energy consumption and grain being blown upward in extreme situations. Poor performance was also caused by the adoption of an incorrect grain layer thickness. Too thick grain layer, in some regions, implied that some grain sections wound not dry evenly because they will be exposed to damp air. If the grain layer is too thin also, most of the air can escape while still removing moisture, resulting in low thermal efficiency (Perré *et al*.

2023). Very elevated air movement speed does not allow the drying air sufficient residency opportunity to absorb moisture from the grain. That results in depressed warm air-drying efficacy. Yet too low blowing air rates result in diminished drying effectiveness also (Miraei Ashtiani and Martynenko 2024). The subsisting lack of precision in predicting the optimum drying parameters for incoming grain, when processing material of diverse initial moisture content at the Concession grain storage depot, renders it difficult to plan and schedule the maize grain drying process at the facility. Establishing a scientifically tested and consistent methodology of determining the cost-effective set of drying plant operating conditions, which assures the yielding of well processed good quality grain, through modelling and simulating the operations of company X as a prototype model of the drying process goes a long way towards mitigating the escalated costs borne from the trial-and-error method of deciding the drying parameters, as is currently happening. That approach of running a grain drying plant is costly, inefficient, and laborious (Perré *et al*. 2023). Therefore, all this calls for the optimization of the grain drying process to improve the reliability of the drying process and obtain the best results in optimum time. The current practice at the plant is that dryer operating parameters are determined from experienced guessing, which is an unreliable and inconsistent approach regarding the drying results. Grain dehydration has considerable energy saving potential, of up to more than 50%, if appropriate control of process parameters and energy recovery techniques are technologically employed (Chojnacka *et al*. 2021). Savings could be more than 50% with proper process control and heat salvage systems are implemented (Dębowski *et al*. 2021). Grain drying is partitioned into three distinct operation processes, which are the drying process heat, the heat transportation, and the heat generation.

Theoretical Background

Grain desiccating is amongst the generally energy-exhaustive business pursuits that pervade the overall process of grain handling in preparation for its long term storage. In accordance with manufacturing industry data, the grain dehydration operation in the industrialised society accounts for as much as 10% to 20% of the total industrial energy consumption (Jimoh *et al*. 2023). The efficacy of the dryer performance hinges on the dehydrated product quality as well as the energy use level of the drying plant (Wang *et al*. 2023), during the grain desiccating process. The energy required for grain moisture mechanical withering is significantly affected by the latent heat of water vaporization, characterized by its huge energy value of 2257 kJ/kg, together with the sensible heat value which must be gotten rid of from the dryer (Jimoh *et al*. 2023). Generally, in conventional dryers, the thermal energy essential for raising the temperature of the product and evaporating the humidity inside the grain is delineated in Eq. 1 (Kaveh *et al*. 2024),

$$E_c = m_p c_p \Delta T + m_w c_w \Delta T + m_w L \tag{1}$$

wherein E_c represents the energy requisite for the grain moisture dehydration (J), m_p denotes the mass of the humidity withered grain (kg), c_p symbolises the explicit thermal energy capacity of the moisture dehydrated grain (kJ/kg), m_w represents the humidity mass extracted from the grain (kg), c_w is the distinctive thermal energy capacity (kg), of the moistness, and L represents the latent thermal energy of moisture evaporation (kJ/kg). In addition, the envisaged efficiency of the drying plant is considerably diminished by rudimentary designs of drying vessels along with ineffective insulation, (Bhattacharjee *et al*. 2024). The depletion of conventional energy resources has created complex energy challenges in the current world order. In this research, the byzantine issues of optimizing the parameters of the maize grain drying process was attempted, and an analytical model was developed in an effort to foster the sustainability economy of this kind of operation by focusing on Concession depot of company X, as a case study. The current operation practice is that experienced dryer operators do experienced guessing of the operating condition settings thereby rendering the quality of the grain output erratic and inconsistent due to lack of typical scientific and technological determination of the parameter settings at the plant.

The temperature disparity relating to the grain with the proximate environments is employed in studying thermal energy conduction through the grain dehydration process. This functions as the motive power which governs transmission of heat between the hotter dryer vessel interior environments onto the cooler grain maize body. The thermal energy transfer mechanisms, during the gain mechanical withering process, incorporates the radiant heat transfer mode, conduction, and convection (Calín-Sánchez *et al*. 2020). The conduction and convection thermal energy transmission mechanisms always are involved, irrespective of the drying infrastructure system in employment for the operation. The energy diffusion, in grain maize drying, is regulated by dint of the subsequent occurrences (Lamidi *et al*. 2019; Bhattacharjee *et al*. 2024): (a) Exterior moisture film mistiness transportation beginning at the grain surfaces headed for the outlet provide the primary propelling desiccation potency; (b) dehydration chamber, outside warmth transference to the grain exterior by means of convection or conduction; (c) intramural heat transmission in the interior of the grain conduction of the required energy for transforming the grain interior moisture into steam, energy by means of conduction; (d) interior moisture is conveyed in either one form - liquid or vapour - states through different mechanisms inclusive of capillary motion for the liquefied phase, and diffusion transmission of molecules in either vapourised or liquefied states. The process is controlled by the gradient slope, driving force, between singly grain moisture content and fractional condensation (vapour) force. Mondal and Sarke (2024) in concurrence with Jokiniemi and Ahokas (2014), determined that diversity of systems coming into play, inclusive of moistness and liquescent diffusion, mistiness diffusion, *inter alia*, moisture is transported from the interior surfaces of the harvest grains to the exterior surfaces. Several vital variable control factors should be judiciously contemplated in an attempt to understand the all-inclusive grain dehydration activity such as drying run time; rate of drying; deep or thin layer thickness of the grain bed; drier efficiency; airflow rate; drying temperature and drying constant, *inter alia*. This experimental study considered three factor – time, temperature, and airflow rate – variation analysis in order to understand how they influence the moisture reduction process in the grain optimally with minimum energy use.

Extraction of moisture from grains, during drying, of whichever form requisites the simultaneous transference of mass as well as heat, which upsets the grains' physical construction outlook and chemical composition (Mahanti *et al*. 2021). The dehydration process performance of these organic products, under any drying circumstance, is assessed by the dry and wet moistness amount computation formulae, respectively, presented in Eqs. 2 and 3 (Kumar *et al*. 2023).

$$MC_{wetbasis} = \frac{M_i - M_f}{M_i} \tag{2}$$

$$MC_{drybasis} = \frac{M_i - M_f}{M_f} \tag{3}$$

A number of studies have been undertaken, and results have signposted the use of elevated desiccating air temperature as offering good prospects for saving energy in the course of grain drying (Chojnacka *et al*. 2021). However, this subsists to a limited extent granted that the maize grain is subjected to drying at exalted air temperature within a constrained range, beyond which the process may start compromising the sustainable viability of the grain. Further research is, therefore, required in order to scientifically establish the good grain quality assuring, drying process control parameters of the maize species processed, (Jokiniemi and Ahokas 2014). Figure 1 shows a chart displaying a number of simulation and modelling different process optimisation phenomena.

Fig. 1. Simulation and modelling methods for optimizing various phenomena (Tayisepi 2017)

One of the fundamental metrics used to appraise the performance of the drying operation is the drying efficiency, which is determined from the comparative ratio of the amount of thermal energy used to remove moisture from the grain batch to the total heat energy. This is the factor known as thermal efficiency, which is also presented as specific energy consumption of the drier

The thermal energy utilization in the drier is established grounded on the electrical power used up in heating the drying environment, as well as the quantity of moisture vaporised, from the grain, per unit period. The electrical energy includes the power for heating the air and powering the heater element. It is presumed that, after considering system heat losses, 50% of the energy is effectually utilised during the process. The power required for the system, to heating the air in the drier (cogitated as the needed energy for the air heater), is computed from Eq. 4 (Natarajan 2022),

$$P_{\mathrm{air}} = C_{\mathrm{a}} \Delta T q_{\mathrm{m}} \tag{4}$$

where P_{air} denotes the heat power in watts (W), C_{a} refers to the air specific heat capacity = 1005 J/kgK C, ΔT is the temperature difference between furnace intake (room temperature) and dryer intake, and q_{m} is the air mass flow rate (kgs^{-1}).

The thermal energy required for evaporation of the moisture from the maize grain is presented in Eq. 5,

$$P_{h_2o}(W) = R * \Delta H_{vap} \tag{5}$$

where R refers to the average amount of water removed in kg/s and the latent heat of water vaporisation ΔH_{vap}, which is 2.26 x 10^6 (J/kg).

Whilst the thermal energy required to heat the maize grain particle is given by the Eq. 6,

$$P_{maize}(W) = m_w * C_p * \Delta T \tag{6}$$

in which m_w refers to the mass flow rate of maize grains (kgs^{-1}), the specific heat capacity of maize is given by C_p, and the temperature change between the moist and dried maize grains is represented by ΔT. The mass flow is computed from the dried maize grain mass per time cycle.

The other factor that constitutes a vital performance metric of the grain demoisturisation process is the drying efficiency, which considers the amount of thermal energy utilized in drying in comparison to the total heat energy expended during the full course of the drying operation. Additionally, the proportion of thermal energy employed in removing moisture from the grains to the overall quantity of heat energy generated by the system used, is termed the drying plant thermal efficiency. The drying plant specific energy use – which is computed by integrating the energy utilisation in removing a quantified amount of moisture – is used to specify the energy efficiency of the dryer. Equation 7 gives the formula for calculating the drying process specific energy consumption,

$$E_{sd} = \frac{E_d}{m_w} \tag{7}$$

where E_{sd} is the drying process specific energy use; m_w refers to the quantity of water extracted by the drying process, and E_d is the energy use of drying air

Generally, the efficacy of the maize grain dryer is computed through apportioning the energy utilised to remove the moisture of the grain kernels (conjectural energy) to the overall energy input to the dehydration machine (heat energy), articulated as a fractional percent, (Natarajan 2022).

A numerical model describes the physical character, as well as the features of a physical entity structure in terms of arithmetical mutable representation symbols and operators. Contingent upon the groundwork on which the representation is developed, arithmetic representations can be generally partitioned into physical science-grounded and observation-based depictions. Numerical representations assist in getting clearer understandings into the performance of the entity being modelled. Signal-to-noise (S/N) ratio investigation is an essential component of this procedure (Tayisepi 2017). The methodology is broadly established in optimising stratagems, materials, processes, and equipment. The regulating constraint factor intensities are assessed for improved outcomes through maximising the S/N ratio (Tayisepi *et al*. 2024).

The main problem of the existing drying operation is uneven thermal energy circulation in the dryer hollow compartment. This causes the grain in the lower platters to wither more rapidly as compared with those in the top-level trays of the dryer vessel. This resulted in the ensuing complications in the course of grain drying:

Excessive drying of the grains at the lowermost levels of the dehydration kiln damages the endosperm of the grain such that the grain seed loses its ability to germinate. Extended desiccating duration adversely affects the grains at the uppermost level of the drying kiln. Longer than normal exposure period to hot air of grains on the bottommost layer in addition to, prolonged dehydration duration for the grains at the apex layers of the withering vessel, leave the parched grains distinctive in quality, inadvertently leading to negatively impacting the grain general quality. Diminution of the quality due to the presence of excessively withered grains will possibly reduce the market price. A variable quality implies difficulty in forecasting of quality. In addition, the product cannot be relied upon for its usage as seed grain. Hence, optimisation work is of importance and will improve the above problems. The grain dehydrating procedure is grounded in the moisture diffusion beginning at the interior core of the grain towards the exterior surface of the grain. The scorching and dried out air which comes in contact with the grains, leads to the warming of the moisture in the interior of the grains. This leads to the evaporation of moisture from the grains and tending to saturate the surrounding air. The intricate stages of the grain drying dynamics of grain drying are summarised in the successive stages presented in Fig. 2. The grain kernel is primarily launched into the drying chamber under unvarying interior content of moisture. The disparity in moistness level relating to the grain's interior and exterior - which is thermally elevated by the blowing of hot air in the dryer - which raise the surrounding temperature – prompts the grain kernels to undergo the vaporisation of moisture from its inside as the humidity surrounding the grain exterior vaporises. This leads to increased advancement of water from inside the grains to the outside as the grains try to establish new humidity balance in the dryer environment.

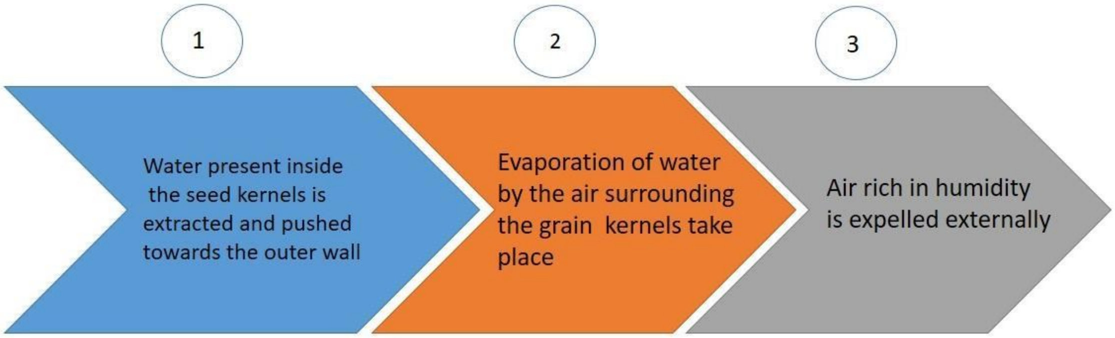

Fig. 2. Successive stages of the grain drying process

Accordingly, through manipulating the stream of heated air as well as the permeability of the grains, moisture is removed from the surface, pursued by the moisture existent inside the body centre of the seed (Fig. 3).

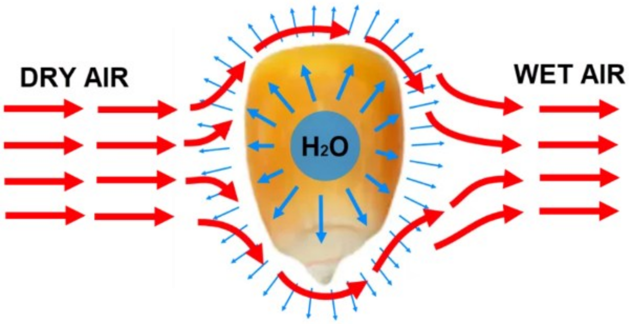

Fig. 3. Warm air and moisture movement on grain (Mecmar 2025)

MATERIALS AND METHODOLOGY

The purpose of the present experimental research was to determine the relationship between grain drying influencing factors and analyzing the grain drying process. The experiments were conducted to establish the relationship between the grain desiccating and the main parameters: drying time, drying temperature, the airflow rate as well energy consumption. The multiple fold objectives of the experimental study encompassed the following: identifying the variable input parameters which dominantly influence the mechanically driven thermal drying process, characterizing the trend of the moisture vaporization process from the grain response parameter indicator as impacted on by the independent factors, modeling the drying process, and establishing the optimum drying process parameter setting levels.

Material

Long season variety maize grain, SC 659 (locally referred to as Nzou, meaning the elephant, seed variety), which is cultivated and produced in the high rainfall agronomical region 2, Mashonaland West Province of Zimbabwe, was selected as the test material. This is characterized as a high yield and sustainably produced maize grain variety in the region due to its suitability with the climate of high rainfall received, for an extended period, in the province during the summer season. A typical snapshot image of the maize grain is shown in Fig. 4. Ideally, the grain should reveal no cracks and should not have a rusty smell.

Fig. 4. Image of maize grain

Equipment and Instruments

Figure 5 shows the mobile drying equipment that was utilized in the tests at the Concession depot. The drying machine had the designation of MC 3/60 R mixed-flow dryer. The grain dryer was the main equipment by which the demoisturization was carried out. Maize grain was pushed into the drying chamber through an auger screw and after filling the chamber, the dryer was then electro-mechanically powered to set the drying chamber bin into rotational movement, with the maize inside. The hot air blown inside the drying chamber elevates the temperature of the moisture inside the grains and causes it to escape to the surface. The hot air then collects the water molecules on the grain surfaces and is blown out of the dryer using a fan. This process repeats itself until the desired moisture content, within the grain, 12.5%, is attained.


Air fan unit

Dryer cylindrical chamber with augur screw mechanism internally assembled

Fig. 5. Portable dryer

The grain dryer needs to be able to precisely determine the moisture content in the grain as well as the temperature (Miraei Ashtiani and Martynenko 2024). During the drying tests, three Trime GWs grain moisture sensors (analysers) were integrated onto the dryer chamber walls with their sensory antennas protruding into the grain space in the chamber, in order to realize precise, continual grain batch average moisture content readings directly. Figure 6 show the GWs sensor configuration set which was used in the experimental process humidity testing.

Fig. 6. Trime GWs Grain Moisture content sensor probe and display screen configuration set

Multiple moisture sensor series configuration support high-level measurement quality through averaging measurement outcomes all through the bulky volume of the monitored maize grain material. The integrated sensors arrangement makes it possible to control huge material volumes and delivers accurate moisture readings at varied moisture distribution in grain products (Flor *et al.* 2022). The individual sensors utilized in this application were heat-resistant and had a high temperature tolerance up to 180 ºC. The sensor design was sealed and had elevated reliability and endurance towards mechanical stresses.

Dryer chamber temperature readings were read through an on-board mounted, 3D IP47 HTS Art. 5020002 rod agromatic temperature sensor (Fig. 7). The sensory rod terminal protruded into the dryer chamber hull at the center height of the dryer, whilst the real-time temperature values were displayed through the sono-view screen. The HTS rod sensor probe features are: length of 100 mm; diameter 5 mm; with mounting thread, M8; connected cable (PTFE) high temperature resistant, minimum 5 m long, shielded, maximum temperature: -50 °C to +200 °C (sensor probe and cable). The measurement precision of the temperature measurement meter was ±3.0. The intent of the experimental investigation was to establish the effective drying process parameters which would ensure consistent realization of enhanced drying efficiency and reduced drying costs.

Fig. 7. 3D IP47 HTS Art. 5020002 rod agromatic temperature sensor

The fan is the functional unit that is responsible for blowing air and circulating it into the drying chamber so that air containing moisture can exit the interior of the dryer unit. Unsaturated air is permitted to flow into the dryer chamber cavity. The airflow velocity was regulated by adjusting the power provided to the air blower. In this investigation, the air flow rate was varied at three levels. Determination of the appropriate magnitude of the fan capacity is a fundamental consideration for establishment of the apposite airflow delivery rate into the dryer chamber. The burner unit, also assembled onto the main dryer chamber unit, was responsible for raising the temperature of the air inside the drying chamber. The desired temperature was set at the burner by selecting appropriate thermal intensity capacity. Three temperature levels were respectively set in this investigation. The burner also served the purpose of increasing the humid potential of the surrounding air, so that the air can carry more water particles that will have evaporated from the grain. The burner used diesel as its fuel. Figure 8 shows the fan and burner units assembled onto the drier, utilized in this study.

Fig. 8. The fan and burner assembly unit

Moisture content of the pre-grain-dryer loaded grain batches were tested, for moisture content level, using the calibrated mobile Pfeuffer HE Lite Moisture Analyser. This is shown in Fig. 9, with sample loaded. Once the moisture level was determined, the grain batch would be loaded into the dryer for the prestorage drying process, under automated continuous monitoring, with the aid of the on-board mounted moisture sensors system. The moisture content of maize was determined using a Pfeuffer Lite moisture analyzer. The moisture meter operates by filling maize into the lower part of the moisture meter and screwing it to close. The instrument, which can measure moisture content up to 30%, then displays the correct moisture in seconds on the display screen.

Fig. 9. Pfeuffer HE Lite moisture analyser

Experimental Conditions and Experimental Process

Table 1 shows the drying tests variable (independent) parameters, which were, respectively, varied at three levels each, as indicated. In the investigation, the three aspects of the drying process, under experimental investigation, that were altered to analyze their effects on the grain moisture content, were drying air temperature, drying time, and airflow rate. Grain moisture content, expressed as a percent value, was the response (dependent) parameter. The selected temperature values were conveniently selected, consistent with the operating temperature values used in practice at the grain storage plant and the indicated technical operating temperature range of the drying equipment at the depot. This tested range was anticipated to offer strong understanding of the optimum operating temperature as also used in practice. Design Expert Version 23.1 statistical software was utilized in planning the experimental process as well as the optimization process.

Table 1. Experiment Process Variable Parameter Levels

Drying Parameter	Symbol	Units	Symbol	Level		
				1	2	3
Drying Temperature	DT	°C	X_1	30	60	110
Drying Time	AT	min	X_2	120	150	180
Airflow Rate	AR	m/s	X_3	1.2	1.5	1.8

Figure 10 shows the schematic arrangement of the experimental setup with the sensory measurement system attached on the drier. During the drying tests, moisture measurements were recorded at two stages. Initially, grain moisture state was recorded just before each batch of grain was uploaded into the drier chamber. Secondly, integrated moisture sensors were used to monitor the inside grain demoisturization process state. Moisture sensor probes were mounted at three different diametrical positions at 120° apart and at vertical positions 50 mm apart within the drier chamber. The lowest placed moisture sensor was vertically positioned at 30 mm from the drier chamber inner wall bottom. Results of the inner chamber dehydration process were set to be captured at 20 s intervals and output through excel sheet recording on an HP laptop linked to the sensors system network through the USB port. The grain moisture content level was determined and presented as a % value, on the humidity display screen.

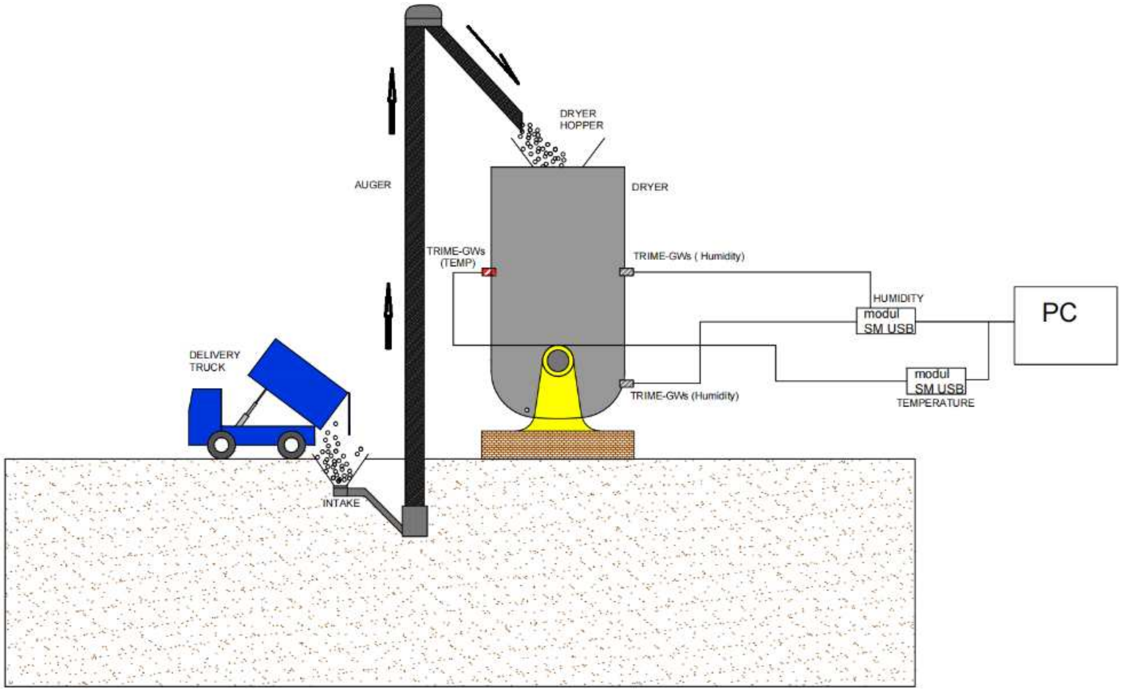

Fig. 10. Experimental set-up schematic arrangement of equipment and instruments

The drier inside temperature was set and monitored with the aid of an on-board mounted temperature gauge. The two temperature sensors were screwed onto the cylindrical body, height center, of diametric opposite sides of the drier with the sensory ends protruding into the grain containing inner chamber. Average temperature value setting and monitoring is vital during the drying process run, in order to ensure that the grain is not over-heated or over dried. The digital temperature gauge display showed the real time temperature readings display of the drying chamber inside as the drying process run progressed. This allowed for adjustments to the temperature level, during the drying process, and made it possible to avoid undesirable circumstances such as grain damage or overheating. Humidity and temperature sensors scanned and recorded the drying vessel chamber interior mugginess and temperature in real time. The sensing devices infrastructure used an ESP32 module-based microcontroller system for the monitoring and controlling the dryer inside environment. The ESP32 building block had gate access elements, which made it compatible in sending the recorded readings data to a database, in which the humidity and temperature sensor reading records are stored on an online on-board running computer that was also utilized as a dashboard displaying the moisture and temperature application recordings, displaying the trend of either parameter in real time. Figure 11 show the schematic flow chart plan of the signal control process. The temperature and relative humidity signal relationships as output from the signal readings of the set experiment signal measuring instruments are represented in Eqs. 8 and 9, respectively,

$$T_{in} = T_{out} = \frac{V_m}{V_{in}} * T_{v,in,} {}^{o}C \tag{8}$$

$$RH_{in} = RH_{out} = \frac{V_m}{V_{in}} * 100,\% \tag{9}$$

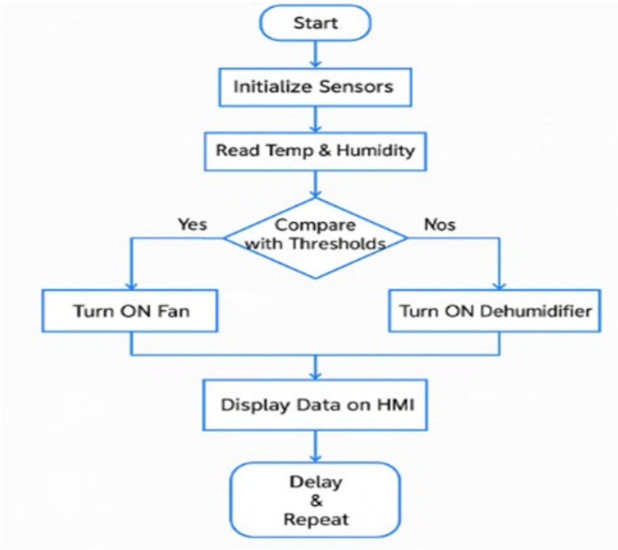

Fig. 11. Schematic flow diagram of the signal control setup

In Eqs. 8 and 9, T_{out} and T_{in}, respectively, are the outlet and inlet temperatures (°C); V_m refer to the measured voltage; V_{in} and $T_{v,in}$ respectively refer to input voltage and standard temperature at input voltage; whilst relative humidity at inlet and outlet, respectively is represented by RH_{in} and RH_{out}. The parameters are recorded as voltage signal and converted to the respective component according to the parameter calibration standard.

RESULTS AND DISCUSSION

A summary of the experimental process results is presented in Table S1 in the Appendices section. Figure 12 presents the inverse relationship between moisture content and drying temperature.

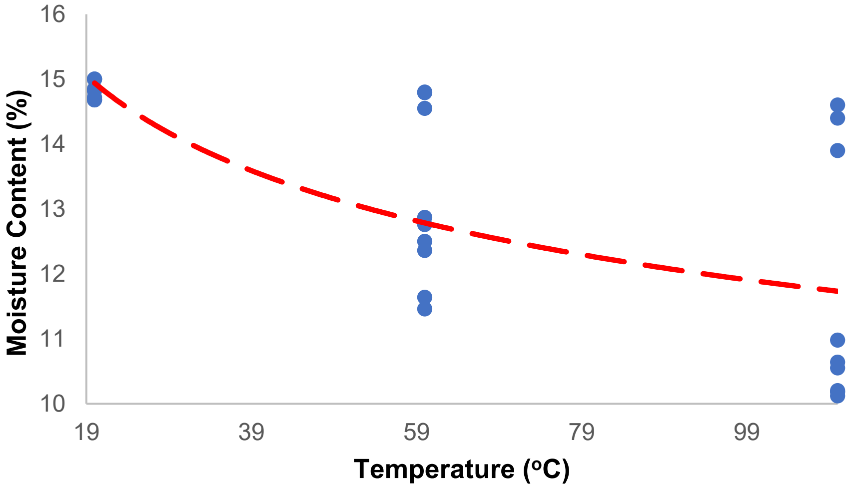

Fig. 12. Moisture content as a function of drying temperature

As the temperature increased from 20 to 100 °C, the moisture content decreased at an accelerated rate. At 20 °C, the moisture content was approximately 15%, and as the temperature rose to 100 °C, the moisture content dropped to around 12.5%. The increase in temperature enhanced the drying rate, which resulted in a faster reduction in moisture content. This accelerated drying process is essential to achieving the desired moisture level efficiently, minimizing drying time and energy consumption.

Figure 13 illustrates the relationship between airflow rate and maize grain moisture content. As the airflow rate increased from 1.2 m/s to 1.8 m/s, the moisture content slightly decreased. At 1.2 m/s, the moisture content was approximately 13.5%, while at 1.8 m/s, it was reduced to about 13.1%. This slight decrease indicates that the increased airflow enhanced the heat transfer and accelerated the moisture removal process from the grain, contributing to the overall drying efficiency.

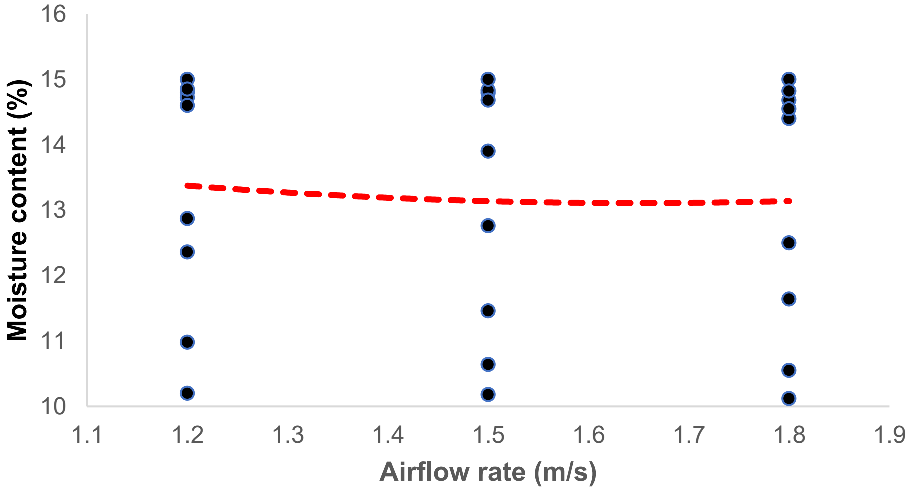

Fig. 13. Effects of airflow on moisture content

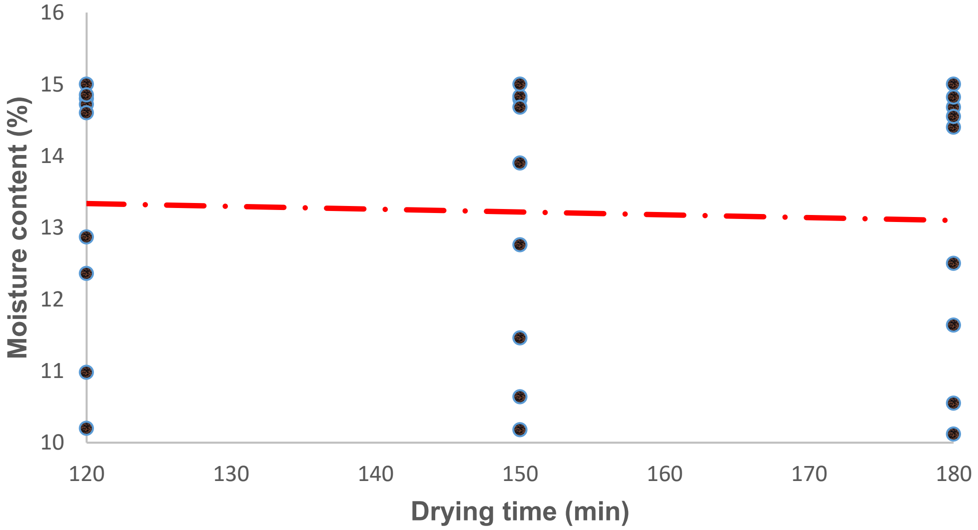

Fig. 14. Moisture content as a function of drying time

Figure 14 shows the minimal variation in moisture content as drying time increased. Despite an increase in drying time from 118 minutes to 178 minutes, the moisture content remained relatively constant, fluctuating only slightly.

This minimal change suggests that drying time had less influence on moisture content compared to the other factors such as airflow rate, implying that once the grain reaches a certain drying point, further time extension does not significantly impact moisture removal.

Figure 15 depicts the relationship between relative humidity and specific energy consumption at three different drying temperatures (30, 60, and 110 °C). As relative humidity increased, the specific energy consumption consistently decreased. At 20 °C, specific energy consumption was around 5.0 MJ/kg, but as the relative humidity rose, it decreased to about 3.5 MJ/kg at 90% relative humidity. A similar trend was observed at 60 and 110 °C as well. This reduction in energy consumption can be attributed to the prolonged residence time of air within the drying vessel. As the air became more saturated with moisture, the drying process became more efficient, requiring less energy to sustain the desired drying process.

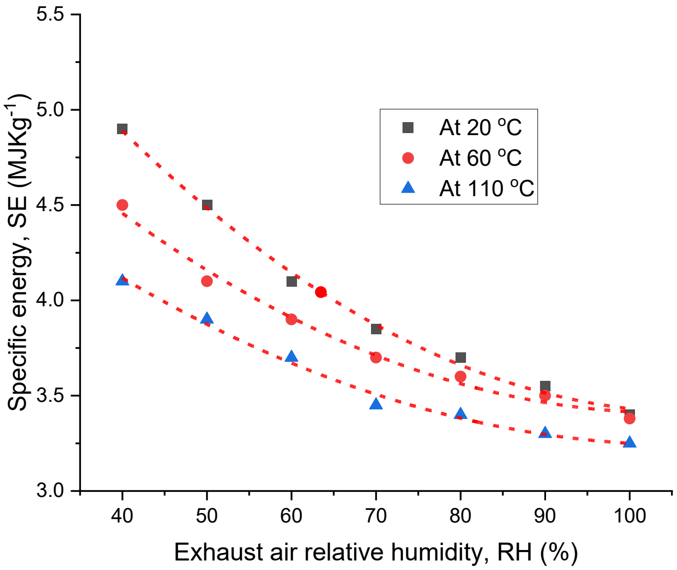

Fig. 15. Specific energy relationship with relative humidity

Analysis of variance (ANOVA), statistical examination was carried out on the experimentally gathered data in order to establish the extent of the influence of the input variable parameters on the output responses as well as the level of significance of the independent variables, in their hierarchy, on the response parameters.

Table 2 presents ANOVA results of moisture content, at 95% confidence level. The P–values of temperature and airflow rate were less than 0.05 (being 0.00 in either case) which show that these two variable factors had significant influence on the mechanized drying process of the maize grain. Time appeared to be a less influential factor, having a P-value of 0.793 as shown in Table 2.

Table 2. Analysis of Variance for Grain Moisture Content

Source	DF	SS	MS	F	P
Temperature (ºC)	2	43.8388	21.9194	30.59	0.000
Time (min)	2	0.3361	0.1680	0.23	0.793
Air Flow (m/s)	2	29.7732	14.8866	20.78	0.000
Error	20	14.3296	0.7165		
Total	26	88.2777			

The Regression model, expressing the relationship of moisture content to the variable parameters, is expressed in Eq. 10:

$$\text{Moisture Content} = 17.304 - 0.03427\ \text{Temp.}(^{\circ}\text{C}) - 0.168\ \text{Time (min)} - 0.01520\ \text{Airflow (m/s)} \quad (10)$$

The model summary, in Table 3, shows the effective representativeness of the data, as confirmed by the coefficient of determination (R^2) value of 83.77%.

Table 3. Model Summary for Moisture Content

S	R^2	R^2 (adj)
0.846451	83.77%	78.90%

Figure 16 presents the interaction plot of factors, wherein it is apparent that all three factors showed interaction behaviour at some point. Thus, all the factor become relevant to show their presence in the mathematical model.

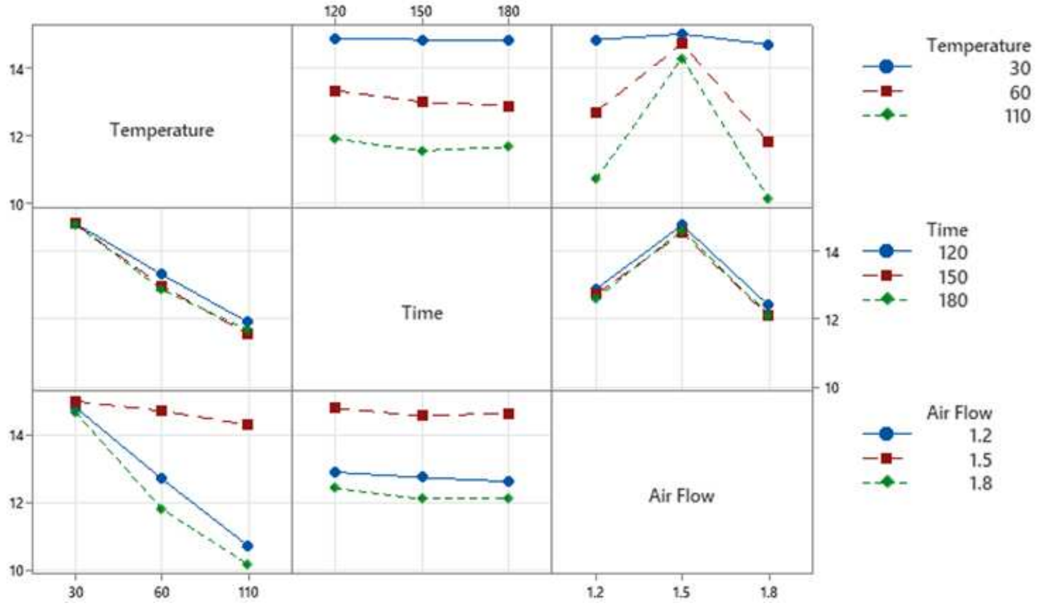

Fig. 16. Interaction plot of factors affecting moisture content

The residual plot in Fig. 17 shows the normal probability plot that denote that the points closely hugging the diagonal line, thereby further confirming the representativeness of the model to the data.

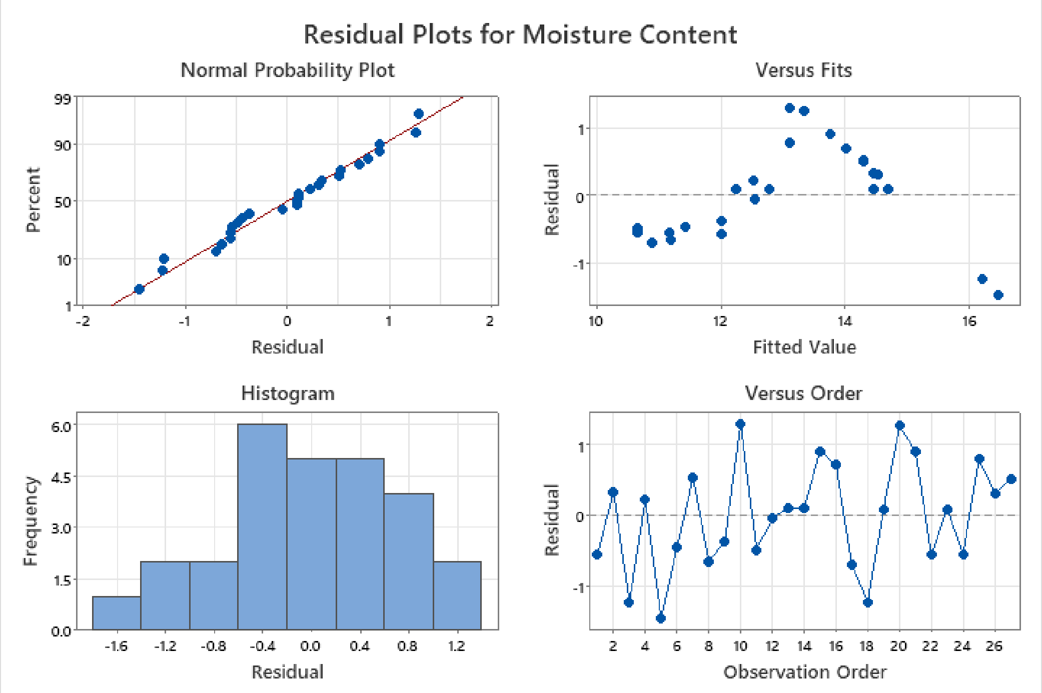

Fig. 17. Residual plot

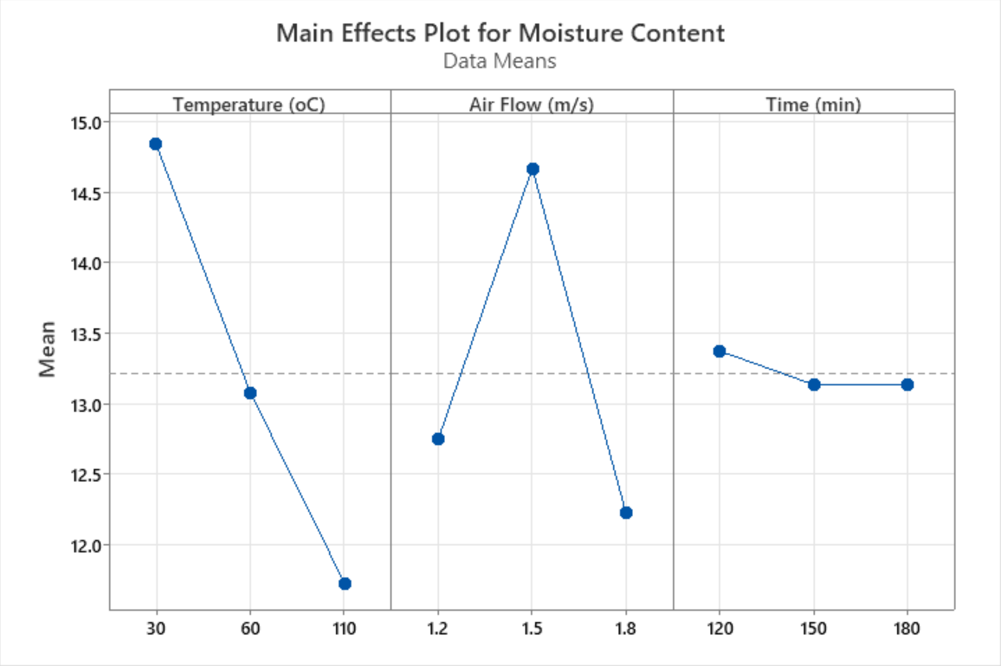

Fig. 18. S/N ratio main effects plot

Optimization analysis was employed for the determination of the operating factors (drying parameters). The main effects plot (MEP) statistical tool was employed (Tayisepi 2017) to set levels for positive influence on the response factor of grain moisture dehydration in minimum cost-effective processing operation, the signal to noise ratio (S/NR). The desirable optimum setting conditions, interpreted from the experiment data results, are shown in Fig. 18. The S/NR were computed using the "smaller is better" condition in order to minimize the costs of the operation under the three input variable conditions. Process optimization is expected to result from energy savings, where appropriate drying air temperature is utilized at energy saving airflow rate. All set drying process control parameters were set such that the combination resulted in elevated exhaust air humidity in minimum operation duration without causing some viability opprobrium in the grain.

The graphically presented optimum drying process values according to the results, in Fig. 18, were the operating temperature of 30 °C, air flow rate of 1.5 m/s, and drying time of 120 min. These were intended to achieve the desired dryness outcome of the grains without causing the grains to potentially lose integrity, reducing seed viability, and causing damage (Ranganathan and Groot 2023).

VALIDATION TEST

Validation experiment runs were carried out by setting the model-determined optimum drying parameters, in the case of the actual drying facility in order to confirm the validity of the predicting capability of the optimisation model practically (Oosthuizen *et al*. 2014). The validation experiment tests demonstrated the functional viability of the optimisation model, as compared with practical data, as shown in Table 4. The predicted optimum values and the practical validation experiment values varied within less than 15%.

Table 4. Validation and Model Results Variation

Drying parameter	Symbol	Units	Model value	Validation test run value	Variation %
Drying temperature	DT	°C	30	34	13.3
Drying time	AT	min	120	115	4.12
Airflow rate	AR	m/s	15	16.8	12

CONCLUSIONS

A drying process for maize grain is essential for maintaining grain quality post-harvest by reducing moisture content. This study focused on optimizing the drying parameters to enhance efficiency and minimize energy consumption.

1. The mechanized drying process of maize grain, under the influence of the three variable operating parameters – drying temperature, air flow rate, and drying time – was experimentally studied, with the goal of establishing cost efficient, cost-effective optimum operating parameters for the moisture dehydration process of the maize grain.
2. Design expert statistical software was applied in planning the empirical experimental study and to analyze the resultant data, which was gathered under technological observation and self-regulation with sensors and related manipulating instrument. The experimental data was analyzed, and the various drying parameters were characterized against moisture content of the grain. The analysis found that air temperature and airflow rate significantly influenced the drying dynamics, whilst in contrast, the drying

time had a minimal impact on the overall process. The optimized drying operation is realized from improving the process efficiency which include energy consumption minimization.

3. The study established the optimum drying conditions being an operating temperature of 30 °C, air flow rate of 1.5 m/s, and drying time of 120 min. Further, the research recommends the implementation of judicious and effectual prestorage loading drying machinery maintenance and operational effectiveness systems should be established to sustain the good quality of maize. Optimally run and efficiently functioning dryers could yield the farmers significantly enhanced revenues from their maize grain product.

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Data Availability Statement

The original contributions presented in this study are included in the article.

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APPENDIX

Table S1. Experiment Process Results

Run Order	Temperature (ºC)	Time (min)	Air Flow (m/s)	Moisture Content (%)	Run Order	Temperature (ºC)	Time (min)	Air Flow (m/s)	Moisture Content (%)
1	110	150	1.2	10.64	14	60	150	1.5	14.8
2	60	180	1.5	14.79	15	30	120	1.8	14.68
3	30	150	1.5	15	16	30	120	1.8	14.72
4	60	120	1.2	12.76	17	110	150	1.8	10.2
5	30	120	1.5	15	18	30	120	1.5	15
6	110	150	1.2	10.98	19	60	120	1.2	12.87
7	30	180	1.2	14.83	20	110	180	1.5	14.6
8	110	180	1.2	10.55	21	30	150	1.8	14.68
9	60	180	1.8	11.64	22	60	180	1.8	11.46
10	110	150	1.5	14.4	23	60	180	1.5	14.55
11	110	180	1.8	10.18	24	110	150	1.8	10.12
12	60	120	1.2	12.5	25	110	120	1.5	13.9
13	60	120	1.8	12.36	26	30	180	1.2	14.85
					27	30	150	1.2	14.82