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The Automated Process Control Model for Energy Consumption Optimization within Plantain Flour Processing Facility

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ABSTRACT

Energy usage is a great concern for industrialists because it is a prime determinant of production cost. When energy consumption becomes a challenge, the industrial production process remains unsustainable. Hence, the need for automating the process control model of the plantain flour processing facility for its energy consumption optimization. Time and motion study was used on the plantain processing plant on a modular basis to develop the control system. The model control system for the plant was simulated and implemented. Experimental runs were carried out, and a system response time of 30 milliseconds was computed. In comparison, the results show that using the automated facility saved 30% more energy than running the plant manually. Thus, contributing control process model as an energy optimization concept for plantain flour plant facility.

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1. Introduction

Science and technology have undoubtedly benefited the manufacturing industry, encouraging both manufacturers and researchers to focus on this promising area to develop tools and equipment with improved efficiency and performance that meet market standards. Automation process modelling has provided numerous benefits in industries such as automobiles, aircraft, textiles, pharmaceuticals, food processing, and domestic control [1]. Samanta et al. [2] noted that the degree and nature of automation in production processes and manufacturing vary. Increased productivity as a result of process automation and drive technologies may not have a negative impact on employment schedules. Industrial automation enables enterprises to integrate systems to reduce or eliminate information and reporting gaps; double entry of information; achieve completely paperless transactions; automatically capture billing and production data; and ensure that key personnel are always up to date on the company's operations.

Automation is defined as a set of technologies that enable machines and systems to operate without significant human intervention, achieving superior performance when compared to manual operations [3].

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This technology is quite different from mechanization, which refers to the use of machines to replace human labor. Automation, in general, is the incorporation of machines into a self-governing system. The manufacturing industry is one of the most important areas where automation technology is used to control industrial machinery. The level of industrial automation varies greatly depending on the type of industry. The automotive and semiconductor industries have been the most advanced in terms of implementing plant automation principles, with nearly all processes being automated and fairly well integrated. At the other end of the spectrum is perhaps the food industry, representing lower levels of automation, which has traditionally lagged behind in adopting technological advances [4]. The incorporation of automation in manufacturing processes has led to increased safety levels for operators as well as work pieces, resulting in increased productivity, improved quality, efficiency, and reduced labor costs as well as human errors. According to Sudeep and Sridhar [5], the basic requirements for process automation include a power source, suitable inputs and outputs, proper feedback, and commands.

Samanta et al. [2] worked on the "automation of a cement process plant" with the aim of eliminating the challenges associated with the manual operation of the plant. This was accomplished by using sensors and timers in conjunction with a Programmable Logic Controller (PLC) to automate all processes in the plant. This resulted in increased output, lower production and maintenance costs, and an eco-friendly process plant. This control system was adopted and modified to automate the plantain flour processing plant. Dhivya et al. [6] automated various agricultural processes, including seeding, ploughing, irrigation, planting, fertilizing, weeding, and harvesting. In this work, the input parameters of each process were controlled and monitored by using PLC along with sensors. This resulted in an increase in agricultural yield as well as a decrease in production cost. Yousif and Dening [7] worked on "automatic control for storage and retrieval systems based on PLC" with the goal of simplifying the storage and retrieval system. This was achieved by automating all the manual operations involved in the system as well as controlling the storage and retrieval of goods from various locations using a three-axis movable rod controlled by a PLC. This resulted in more efficient use of labor and resources, as well as an improvement in the quality of goods manufactured. This study will aid in the automation of the plant's material handling system. Shah et al. [8] investigated the automation of water treatment plants, using PLC to automate all processes involved in water purification. The PLC makes real-time decisions based on the input signals from various sensors placed in different critical locations throughout the plant and sends the decision to the output devices. This eliminated human interference, thereby increasing the accuracy and speed of the processes.

Rathore et al. [9] worked on "PLC based Proportional Integral Derivative (PID) implementation in process control of temperature flow and level." The study provided a solution to the problem encountered when using a PID controller to control the temperature of a system. This was accomplished by combining a PID controller design with a PLC to efficiently control the time required to heat up a specific solution to a desired temperature while maintaining system stability. This improved the system's accuracy. Kumar et al. [10] investigated the use of PLC in the automation of a biogas plant. In this work, various parameters influencing the system's processes were controlled and monitored using sensors in conjunction with a PLC. This increased the efficiency of the biogas plant. Jijo and Ramesh [11] worked on process automation of a parotta plant. In the study, all the manual processes in the cooking and cooling processes of the parotta process plant were automated using sensors and variable frequency drives in conjunction with PLC. As a result, labor, waste, and production costs were reduced. The control system can be adapted for use in the automation of a plantain processing plant, particularly in the washing and drying sections.

A control system was developed by Patel et al. [12] for automating a chemical processing plant. PLC and Supervisory Control And Data Acquisition (SCADA) were introduced into the process plant in the study to convert the manually operated plant to a fully automated plant, thereby increasing productivity and replacing humans in tasks performed in a hazardous environment. The control system can be modified and adapted in the drying section of the plantain flour processing plant. Kanimozhi et al. [13] worked on a "PLC controlled automatic food packaging machine" as well. In the study, a small and simple packaging system was designed and fabricated using PLC software, as well as implementing the new techniques called HMI for touch screens. When compared with the manual system, the designed system reduced time and increased production rate. Bhiungade [14] worked on conveyor automation using PLC with the aim of ensuring effective conveyor belt monitoring and control. This was achieved by controlling the conveyor with a sensor, which increased the conveyor's efficiency. This concept will be helpful in the automation of material handling systems in the plantain flour processing plant. Vans and Kumar [15] developed a control system that regulates the speed of a fan based on the temperature of a room. In their work, PLC and various types of sensors were used to control various parameters such as temperature and speed. This improved the system's accuracy.

Aside from the hygiene promotion associated with the control system and its timely delivery of machine operations, it has also been established that an excellent arrangement of control systems on the production shop floor could help in controlling the usage of energy required for operating the air conditioning system of the manufacturing industry [16]. In addition, Peter and Mbohwa [17] proposed a framework for the sustenance of energy conservation using emerging strategies in the thermal, materials, and waste processes. While Zeng et al. [18] examined and audited the factors required for fuel consumption to achieve optimal factors that aid in the reduction of the fuel consumption rate. Kelly et al. [19] demonstrated energy conservation in dairy farming facilities by incorporating gas turbines and an arrangement of solar cells and light-emitting diodes into farm facility energy management. Opoku et al. [20] also used a time-series model algorithm to optimize industrial electricity consumption by modelling historical data; the results were very encouraging.

However, there is a gap in the use and application of automation for energy conservation that must be filled. As a result, this study presents the automation process modelling of a plantain flour processing plant, as well as the energy conservation achieved through the use of control systems and a comparative analysis of the energy consumption approach for an industrial plant operating in both manual and automated modes. Thus, contributing energy optimization or saving model to the industrial facility for the processing of plantain flour.

2. Methodology

This section provides a brief description of the processing plant and the devices used to implement the automation process of the plant.

2.1 System description

The process plant is divided into six sections, namely: washing, grating, drying, milling, cooling-conveying, and packaging sections, as shown in Figure 1 and Table 1. The washing section begins operation as soon as the plant is turned on, waiting for unpeeled or peeled plantain pulps to be loaded before the washing process starts. When the contact switches at the two ends of the washing section's conveyor belt are not activated, the washing section stops operating. After washing, the grating section begins operation as soon as the contact sensor is activated by plantain. When the limit switch located between the grater and the rotary dryer detects no flow of grated plantain from the grater, the grater stops operating. The rotary dryer begins to rotate when moving grated plantain pulp actuates the limit switch located between the rotary dryer and grater after it has been pre-heated to 65°C. After drying, the hammer mill starts immediately after the dried plantain pulp actuates the limit switch located between the ham-

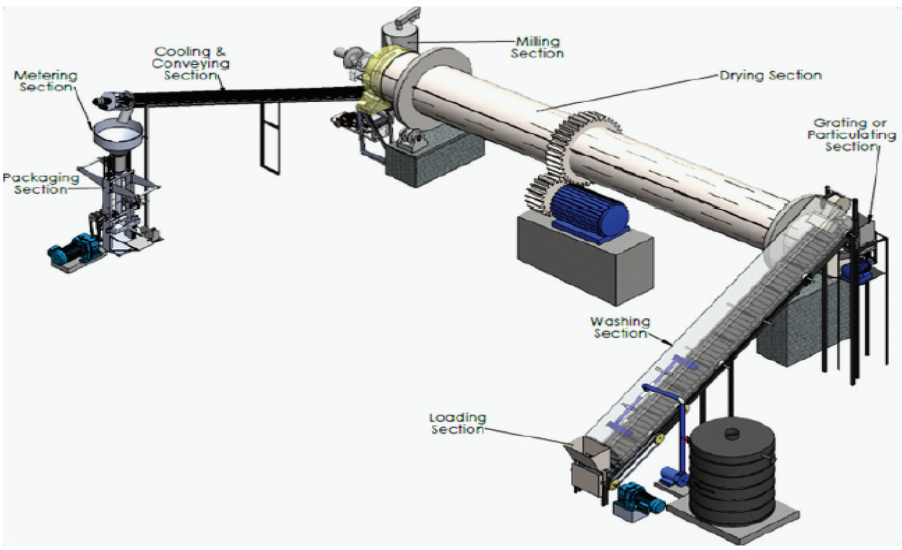

Figure 1. The automated plantain flour processing plant

mer mill and the rotary dryer and stops operation when the limit switch located between the screw conveyor and the hammer mill detects no signal. The cooling-conveying section starts when the limit switch between the screw conveyor and the hammer mill is actuated and stops when the limit switch between the section and the packaging section detects no signal. The packaging machine begins operation when the limit switch between it and the cooling-conveying section is actuated. The weight sensor located on the control valve of the packaging machine ensures that no more or less than the inputted weight of plantain flour is bagged.

2.2 Materials

The control system is composed of various components. The materials after careful consideration, were position sensing devices, load cells, temperature sensors, electrical contactors, relays, liquid-crystal display (LCD), switched-mode power supply (SMPS), and electrical wires selected to effectively control the process plant. These materials, which perform different functions, are coordinated by the controller. As a result, the materials in Table 1 were carefully selected to meet the requirements of this work based on functionalities and control parameters.

2.3 Control system implementation

As shown in the process control system architecture model for the plantain flour processing plant, a modular approach to automation was used, with each machine treated as a single module with its own controller (Figure 2). The system process as modelled in the flow chart of Figure 3 is a projection of the system description as contained in section 2.1. This gives the operational activities of the industrial plant under automation implementation of the control system.

3. Results and Discussion

The testing of the developed control system, the energy utilization by the industrial plant, and its comparison are discussed in this section.

Table 1. Control Parameter for Plantain Flour Processing Plant

S/N	Machine	Function	What Parameters to Control?	Control Device(s)
1	Washing	Loading, washing and pre-drying	Gear motor, water pump and heater-blower device	Temperature and Contact sensors
2	Grating	Size reduction for proper drying	Gear Motor	Limit switch and contact sensor
3	Drying	Drying	Heater and gear motor	Limit switch
4	Milling	Pulverization	Electric motor	Limit switch
5	Cooling/con-veying	Conveying and cooling	Gear motor and Blower	Limit switch
6	Packaging	Filling, bagging and sealing	Servo motors, gear motor and electric motor	Limit switch, weight sensor and contact sensor

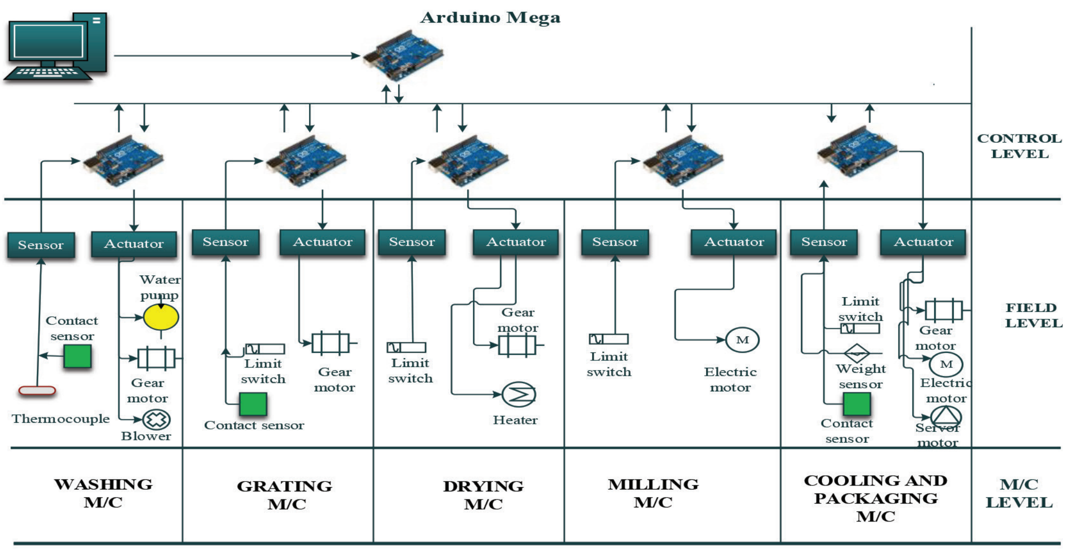

Figure 2. Control System Architecture Model

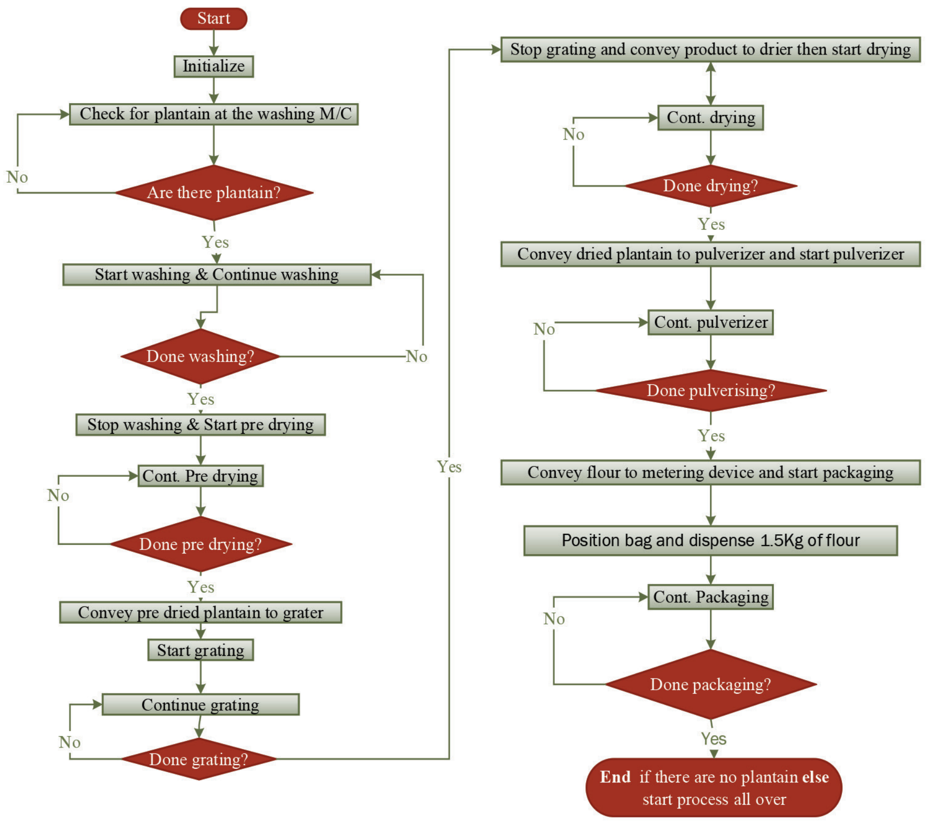

Figure 3. Process model flow chart for plantain flour process plant automation

3.1 Rotary dryer sensitivity test report

The rotary dryer of the process plant is controlled by a thermostat and controller via the sensors attached to the machine. The dryer has a drying range of 0-150°C controlled by a thermostat, making the machine suitable for drying different agricultural products at temperatures within the dryer's temperature range. The rotary dryer's heater and gear motor were turned ON and OFF using a limit switch. Several tests were run with fresh plantain on the limit switch. The limit switch detected wet plantain in each of the tests (Table 2), triggering the heater and gear motor for the dryer's rotary motion.

3.2 Milling and cooling machines' sensitivity assessment

The milling machine is a hammer mill powered by an electric motor, which is controlled by the controller based on the information provided by the limit switch sensor. Based on the sensed value in the milling machine's hopper, the controller automatically turns OFF or ON the milling machine. The sensitivity of the limit switch sensor is shown in Table 3. The implication of this is that, unless otherwise specified, the hammer mill will remain deactivated until dried plantain in the hopper is detected. The system was tested by introducing dried plantain into the hopper

Table 2. Results for the sensitivity of rotary dryer

Runs	Dryer condition	Heater	Gear motor	Remark
1	Not loaded with fresh plantain	OFF	OFF	Passed
2	Loaded with fresh plantain	ON	ON	Passed
3	Loaded with fresh plantain	ON	ON	Passed
4	Not loaded with fresh plantain	OFF	OFF	Passed
5	Loaded with fresh plantain	ON	ON	Passed
6	Not loaded with fresh plantain	OFF	OFF	Passed
7	Not loaded with fresh plantain	OFF	OFF	Passed
8	Loaded with fresh plantain	ON	ON	Passed
9	Loaded with fresh plantain	ON	ON	Passed

five different times to see if the limit switch would respond to changes in the hopper, and the results show that it does.

Excessive heat has an adverse effect on the nutritional content of agricultural products. As a result, the cooling-conveying machine cools the plantain flour as it exits the milling machine in order to preserve the nutritional value of the flour. A gear motor and blower are components controlled in this section by the controller via the limit switch sensor. An experiment was conducted to evaluate the effectiveness of the limit switch sensor in controlling the machine. The result obtained for this section is shown in Table 3. The sensor responded as programmed or expected (four times out of five, which is an 80% accuracy).

Table 3. Sensitivity of the Limit switch to impulse and cooling machine responses

Runs	Milling machine responds to impulse	Cooling machine responses	Remark on cooling machine
1	Yes	1	System detects high temperature and switch ON blower
2	Yes	1	System detects high temperature and switch ON blower
3	Yes	0	System fails to detect high temperature; blower remained OFF
4	Yes	1	System detects high temperature and switch ON blower
5	Yes	1	System detects high temperature and switch ON blower

3.3 Packaging machine load cells validation

The packaging machine, which consists of a screw metering device, is controlled by the controller via the load cell sensor. The load cell is set to weigh 1.5 kg, and plantain flour is metered into a bag that is placed on the load cell. The control is achieved by the operation of the load cell controlled by the controller to turn OFF or ON the gear motor which controls the screw metering device. The quantity of plantain flour metered into the container was validated using a metering scale. Table 4 shows the validation results for the load cell sensor. Ten (10) test runs were performed on the load cell, with seven (70%) passing and three failings. The failed test runs were suspected to have been caused by an environmental factor (wind).

Table 4. Results for the validation of the Load Cell Sensor

S/N	Set weight (kg)	Result
1	1.0	Passed
2	1.0	Passed
3	1.0	Passed
4	1.0	Failed
5	1.0	Failed
6	1.5	Passed
7	1.5	Passed
8	1.5	Failed
9	1.5	Passed
10	1.5	Passed

3.4 Control system performance

The performance of the control system influences response time and system configuration management. A digital stopwatch was used to determine the response time of the control system. An average of 30 milliseconds was obtained for all machines. This was accomplished by activating the limit, contact, and weight sensors of the system. Based on the method of implementing the developed control system as shown in the system architecture (Figure 2), it takes the controller 30 milliseconds to process any measurement of a physical quantity (analog input) sensed by any of the sensors on each machine and take the necessary action (turn ON or OFF electric motor) within the same 30 milliseconds.

3.5 Energy consumption analysis

An energy audit was performed on each machine, with an energy meter reading the current and voltage of electrical components such as heaters, gear motors (3), electric motors (2), and servo motor (1). The power and energy consumed were calculated using Equations (1) and (2). Where V stands for Voltage (volt), I stands for Current (Amp), and T stands for Time (h). The computed power consumption is shown in Table 5.

$$Power = VI \tag{1}$$

$$Energy = IT \tag{2}$$

The energy consumption of the rotary dryer, milling, cooling, and packaging machines after 30, 40, 50, and 60 minutes of operation is shown in Table 6. The results obtained revealed that approximately 114 kJ, 152 kJ, 190 kJ, and 228 kJ of energy were consumed

Table 5. Electric Power Consumed for Drying, Milling, Cooling and Packaging Machines

Machine	**Drying Machine**		**Milling M/C**	**Cooling and Packaging Machine**		
Component	Heater	Gear Motor	Electric Motor	Electric Motor	Gear Motor	Servo Motor
Current (I)	7.50 A	2.51 A	3.72 A	3.72 A	2.51 A	0.45 A
Voltage (V)	190 V	190 V	190 V	190 V	190 V	12V DC
Power (V×I)	1425.0 W	476.90 W	706.80 W	706.80 W	476.90 W	5.22 W

Table 6. Energy Consumed by the rotary dryer, milling machine and cooling & packaging machine

S/N	Time (Min)	P_r (W)	E_r (J)	P_m (W)	E_m (J)	P_{cm} (W)	E_{cp} (J)
1	30	1901.9	57057	706.80	21208	1188.92	35667.6
2	40	1901.9	76076	706.80	28272	1188.92	47556.8
3	50	1901.9	95095	706.80	35340	1188.92	59446.0
4	60	1901.9	114114	706.80	42400	1188.92	71335.2

Legend: P_r, P_m, P_{cm} represent the power utilized by rotary dryer, milling machine, cooling & packaging machine
E_r, E_m, E_{cp} are the energy consumed by rotary dryer, milling machine, cooling & packaging machine

when the process plant was run for 30, 40, 50, and 60 minutes, respectively. Figure 4 shows a graphical presentation of energy against time for the three key/critical machines in the process plant. According to the results obtained, the rotary dryer consumes the most energy because of its heating element, as shown in Figure 4.

However, it is worthy to note that the manual operation of the plantain flour plant under the four different loading capacities of 63 kg, 83 kg 104 kg and 150 kg was initially documented before the implementation of the control process as reported in this manuscript.

Comparatively, the cumulative energy consumption under four different loading capacities of 63 kg, 83 kg, 104 kg and 150 kg at both manually operated mode and the automated platform is presented in Figure 5. Equation (3) was used to compute the percentage of the energy conserved at the various loading capacities using the manual and the automated platforms relatively.

$$E_{cp} = \frac{M_{EC} - A_{EC}}{M_{EC}} \times 100\% \tag{3}$$

Where E_{cp}, M_{EC}, and A_{EC} are percentage of energy conserved, energy consumed during manual operation and energy consumed when the plant was automated respectively. The percentage of the energy conserved is as presented in both Figure 5 and Table 7.

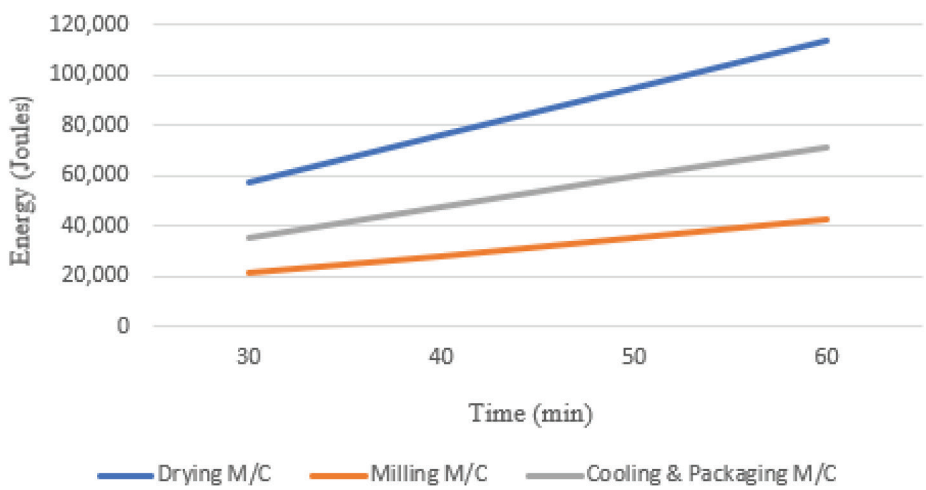

Figure 4. Energy consumption by the key machines in the plantain process plant

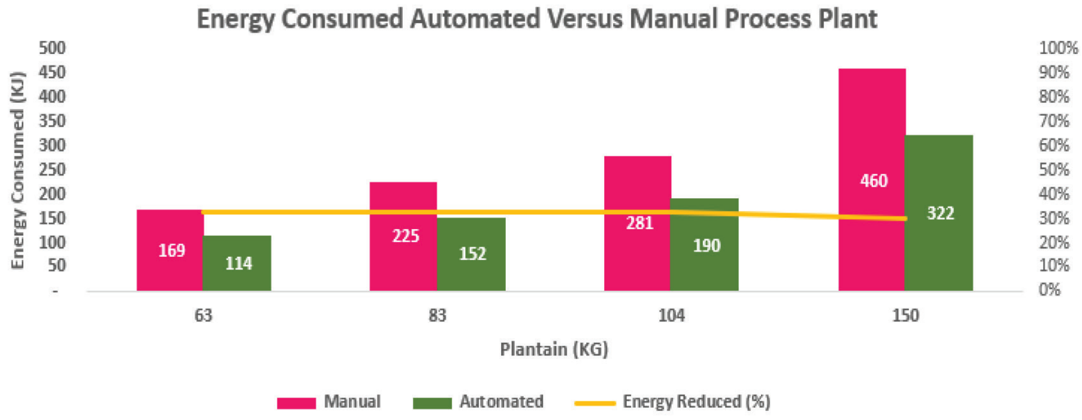

Figure 5. Comparison of energy consumption for manual and automated operation

Table 7. Percentage of energy conserved through automation over manual mode operation

Loading capacity (kg)	Energy consumed at each mode of operation (kJ)		% of Energy conserved
	Manual	Automation	
63	169	114	32.54
83	225	152	32.45
104	281	190	32.38
150	460	322	30.00

For clarity, in Table 7, the result shows that when the process plant was connected to the designed control system, it consumed approximately thirty percent (30%) less energy than when it was manually operated.

4. Conclusion

In this study, an automatic control system technology was used to automate a plantain flour processing plant. The plant's control system was developed using the Arduino Mega 2586 as the controller. The developed control system was implemented based on the control architecture, with a derived response time of 30 milliseconds. Unlike the manual operation, which only takes one set temperature at a time, the control system provides automatic multi-stage drying for the product between the drying ranges of 0-150 °C with a single program, making it suitable for drying different agricultural products within the drying range of the machine. The results show that the control system successfully prevents the process plant from running idle because the controller turns the machines OFF or ON based on the analog readings from the sensors at the field level. The findings are consistent with several recent studies on the advantages of automation in the manufacturing industry.

Similarly, a study using a control system demonstrated that automated processes, if well and effectively deployed on machinery, will reduce the total energy consumed for the production process and promote product hygiene, saving approximately 30% over the use of manual operation for industrial plants. Furthermore, because energy utilization accounts for a significant portion of production costs, production costs would be significantly reduced.

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