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Development and Performance Evaluation of a Nano Sensor Integrated Smart Oven for Enhanced Thermal Control and Energy Usage

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***Abstract*: The advancement of precision cooking technologies has driven increasing interest in intelligent thermal systems capable of achieving real-time monitoring, improved efficiency, and enhanced user safety. Motivated by these challenges, this study presents the development and performance evaluation of a smart oven integrated with a real-time nano temperature sensor, aimed at enhancing monitoring and thermal control. The primary aim is to address the limitations of conventional heating systems, particularly poor temperature stability, energy inefficiency, and delayed feedback response, by leveraging nanoscale sensing and intelligent control algorithms. The smart oven was designed and fabricated using a galvanized steel heating chamber measuring 320 mm × 320 mm, thermally insulated with 10 mm fiberglass to minimize heat losses. The system operates using a 12 V DC rechargeable battery and delivers a heating capacity of 600 W, enhancing portability and off-grid usability. A proportional–integral–derivative (PID) controller was incorporated to achieve accurate temperature regulation. The nano-based temperature sensor offers high-resolution, real-time thermal feedback essential for fine control. The combined hardware–software architecture was evaluated through controlled thermal experiments comparing the nano sensor–based system with a conventional sensing arrangement. Results indicate performance enhancements when the nano temperature sensor is employed. Temperature–time profiles show that the smart oven reaches and maintains thermal equilibrium more rapidly than the conventional setup. Energy-loss curves indicate substantially lower dissipation, while statistical analysis confirms significant differences between the two systems in temperature stability and energy usage. At a benchmark temperature of 120 °C, the nano sensor system achieved approximately 80% reduction in energy loss, a 79.39% decrease in power loss, and a 29.41% reduction in overall energy consumption relative to the conventional sensor. These improvements demonstrate the effectiveness of nanoscale sensing technologies in achieving precise thermal management, reduced energy demand, and greater operational reliability. The implications of this work extend to the broader field of smart culinary and heating appliances, highlighting the value of integrating nanotechnology-enabled sensors with intelligent control techniques to produce energy-efficient and performance-consistent systems. Future research will emphasize deeper sensor integration, optimization of adaptive control algorithms, and scaling of the prototype for industrial and commercial food-processing applications, where precise, efficient, and reliable thermal regulation is essential.**

***Keywords*: Smart oven, Nano temperature sensor, Real-Time monitoring, Energy effectiveness.**

1. Introduction

The increasing demand for intelligent, energy-efficient appliances for both residential and industrial applications has propelled advancements in thermal system design, sensing technologies, and automation. Conventional electric ovens, despite their extensive use in domestic and commercial settings, frequently demonstrate limitations including delayed thermal response, temperature overshoot, uneven heat distribution, and elevated energy consumption resulting from insufficient sensing and feedback control systems (Adeyemi & Oladokun, 2020). These inefficiencies undermine thermal performance, diminish culinary quality, and elevate operational costs. Enhancing thermal regulation and optimizing energy consumption have consequently emerged as key priorities in appliance engineering, especially within the framework of global energy sustainability and smart home integration.

Nanotechnology offers significant potentials for improving the efficiency of thermal devices. Nano-sensors, recognized for their exceptional sensitivity, swift response times, and compact design, offer superior temperature measurement capabilities in comparison to traditional thermocouples and resistance-based sensors (Singh & Gupta, 2021). Their capacity to acquire high-resolution thermal data facilitates real-time monitoring and underpins intelligent control algorithms that can modulate heating elements with greater efficiency. Integrating nano-sensors into oven systems can thus effectively resolve longstanding issues related to thermal non-uniformity, thermal latency, and suboptimal energy utilization.

Recent developments have seen the creation of intelligent ovens featuring integrated sensors, microcontrollers, and Internet of Things (IoT) functionality, demonstrating significant potential in automated cooking, precise heating, and intuitive user interfaces (Rahman et al., 2022). Nevertheless, the majority of current systems depend on macro-scale sensors that do not possess the resolution necessary for detailed thermal profiling. This constraint may result in ongoing problems

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*Corresponding author: adogunsola@lautech.edu.ng including localized temperature, elevated energy consumption, and inadequate safety assessments during operation (Martínez & Perez, 2023). Therefore, a research void persists in the utilization of nano-sensor technology for the development of more intelligent, energy-efficient ovens with improved thermal stability. Sangotayo and Hunge (2020) examined the impact of nanoparticle concentration on the thermo-physical characteristics and heat transmission efficacy of nanofluids within a square cavity. The results endorse the optimization of thermal systems, augment energy efficiency, and refine the design of sophisticated cooling and heating apparatus utilized in electronics, solar collectors, and industrial thermal management applications.

He et al. (2022) developed an advanced microwave device for reheating and defrosting that incorporates an infrared array sensor and a humidity sensor, utilizing fuzzy logic to assess the food's condition, estimate energy requirements, and control the temperature elevation. Their findings illustrate improved food quality and greater energy efficiency compared to traditional time-based methods, highlighting the importance of multi-sensor integration in culinary appliances. Beyond microwave applications, a real-time monitoring system for a sealed electric oven was developed using National Instruments hardware to measure temperature and humidity, in addition to capturing data for process optimization (Popescu et al., 2017). The authors noted that enhanced regulation of temperature profiles reduced both cooking time and energy consumption, emphasizing how measurement resolution and feedback precision directly influence efficiency.

Chukwutem and Lawrence (2025) designed a multi-modal, IoT-enabled smart oven specifically optimized for seafood processing. Their system integrates dual-zone heating, advanced temperature control algorithms, and remote monitoring via Telegram messaging, with the objective of maintaining consistent product quality and improving energy efficiency in industrial environments. This work demonstrates the progression from fundamental household appliances to sophisticated smart ovens equipped with advanced control capabilities. Patents and associated research also demonstrate an increasing trend toward network-enabled appliances.

Concurrently, substantial advancements have been achieved in the development of nanomaterial-based temperature sensors aimed at attaining high sensitivity, swift response times, and seamless surface integration. Phadkule and Sarma (2023) offered a thorough overview of recent developments in nanocomposite-based flexible temperature sensors, including polymer–nanoparticle composites, carbon-based additives, and metal-oxide nanomaterials. These devices exhibit improved thermal sensitivity and mechanical flexibility compared to conventional sensors, highlighting their considerable potential for integration into curved or constrained structures such as oven cavities. Thorough assessments of flexible temperature sensors underscore the importance of metals, metal oxides, carbon nanomaterials, and two-dimensional materials in achieving high sensitivity, flexibility, and long-term stability (Liu et al., 2024; Nag et al., 2022). They highlight fabrication techniques such as inkjet printing and sputtering that are appropriate for large-scale, cost-efficient integration, which is vital for domestic appliances.

Li et al. (2025) reported an ionogel-based temperature sensor with a sensitivity below 0.01 °C and exceptional stability, highlighting the potential of engineered nanoscale interactions for high-precision thermal detection. Nature Similarly, industrial-grade graphene films have been investigated as distributed temperature sensors for industrial coatings, enabling continuous temperature monitoring over large surface areas (Siconolfi et al., 2025). These advancements illustrate that nanomaterial-based temperature sensors can be slender, conformal, and highly sensitive, making them appropriate for lining the interior of an oven or incorporating into structural elements, in contrast to dependence on multiple cumbersome point sensors. Nonetheless, most nano-sensor research is concentrated on wearables, biomedical monitoring, or industrial surfaces, rather than high-temperature culinary settings.

This literature identifies several gaps that underpin the development of the nano-sensor-integrated smart oven: Nano-enabled temperature sensors have been extensively developed for flexible electronics, wearables, and biomedical or industrial monitoring; however, their integration into domestic thermal appliances remains largely unexplored. Addressing these deficiencies requires the development of nanomaterial-based temperature sensors optimized for high-temperature operation, along with advanced thermal control algorithms that facilitate precise and energy-efficient cookery. Experimental performance evaluations comparing smart microwaves integrated with nano-sensors to traditional designs are currently under investigation, it evaluates the Nano- Sensor-Integrated Smart Oven compared to a conventional sensor-based oven system. The study on the development and performance evaluation of a nano-sensor-integrated smart oven is thus closely aligned with current advancements in smart appliance technology, nano-sensing methods, and energy-efficient thermal systems. The current study focuses on the design and performance assessment of a nano-sensor-integrated smart oven, intended to enhance thermal regulation and reduce energy usage. The system integrates nano-sensors for real-time temperature monitoring, an advanced control board for adaptive heating regulation, and embedded algorithms to enhance thermal uniformity. Performance evaluation encompasses thermal distribution analysis, response time measurement, energy consumption profiling, and comparison with traditional oven systems. By incorporating nanoscale sensing technology with advanced thermal regulation systems, this research advances the development of intelligent appliance design and promotes sustainable household energy management. The results offer valuable insights to appliance manufacturers, researchers, and the wider domain of smart home technologies.

2. Materials and Methods

A. Design concept and System Overview

An improved rechargeable portable electric oven was designed, fabricated and evaluated for off-grid baking applications. The system consists of a double-walled metallic housing with fiberglass insulation, an electrical resistance heating element, a rechargeable 12 V battery (62 Ah), a temperature controller, indicator LEDs, and a power switch. The design objectives were: (i) to achieve a target baking temperature of 120 °C, (ii) to minimize thermal losses through appropriate insulation, and (iii) to ensure sufficient battery runtime for typical small-batch baking cycles. The oven has an outer cubic dimension of 320 mm × 320 mm × 320 mm and an inner galvanized-steel cavity of 300 mm × 300 mm × 300 mm, leaving a nominal insulation layer of 10 mm on all sides. The methodology is structured to ensure accurate measurement of temperature response, energy consumption, and energy loss during operation.

B. Materials Selection

1) Mechanical Materials

The outer housing was fabricated from galvanized steel sheets (ASTM A653/A653M) to provide corrosion resistance and adequate formability. The main structural frame and support members were made from mild steel plate (ASTM A36; ISO 630), selected for its mechanical strength and weldability. Thermal insulation between the inner cavity and outer shell was provided by fiberglass (ASTM C553), chosen for its low thermal conductivity (≈0.04 W m^{-1} K^{-1}), high temperature resistance (≥200 °C), and non-combustibility. Standard coated welding electrodes were used for joining the steel components. The external surfaces were coated with a high-temperature protective paint (ASTM D2485; ISO 12944) to improve durability and reduce corrosion; only non-toxic coatings were used for any surfaces that could indirectly influence the cooking space.

2) Electrical and Electronic Components

A Nichrome resistance heating element, compliant with IEC 60335-2-36, was employed as the primary heat source. A 12 V, 62 Ah rechargeable battery (e.g., lead–acid or Li-based, compliant with IEC 62133 and UL 2054) supplied power to both the heating element and control circuitry. Heat-resistant copper conductors, meeting IEC 60227, IEC 60228 and SON NIS 182, were used for internal wiring. Temperature measurement was performed using a Type-K thermocouple (ASTM E230/E230M; IEC 60584) placed at the geometric centre of the oven cavity. A low-voltage switch (IEC 61058-1) controlled power to the heating element, while soldered LEDs (IEC 60825-1) served as status indicators (e.g., power on, heating, low battery). All electrical and electronic components satisfied the relevant SON NIS standards for safety and performance.

C. Fabrication Procedures

1) Mechanical fabrication

Mild steel plates were cut into 320 mm × 320 mm panels using a powered saw and clamped in a bench vice to ensure dimensional accuracy. The panels were welded to form a cubic outer frame of 320 mm × 320 mm × 320 mm. An inner cubic cavity of 300 mm × 300 mm × 300 mm was then constructed from galvanized steel and fixed inside the frame, maintaining a uniform gap of approximately 10 mm for insulation. Fiberglass insulation was cut to size and installed into the gap between the inner and outer shells, including the door. Handles, hinges, and supports for the baking tray and battery stand were installed. Finally, the external surfaces were cleaned and painted with high-temperature protective coating, while the interior galvanized surface remained unpainted to avoid contamination. Exploded view of a smart Oven using AutoCAD software is presented in Figure 1 and Figure 2 presents Isometric view of the oven.

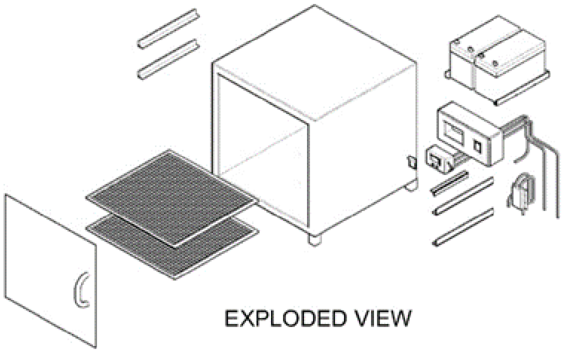

Fig. 1. Exploded view

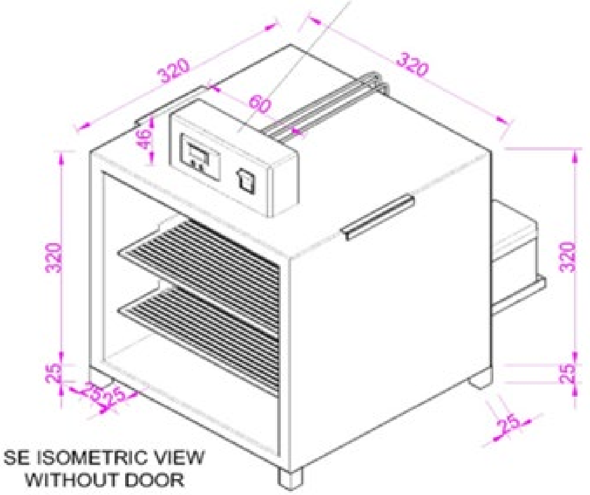

Fig. 2. Isometric view of the oven

D. Thermal Design and Analytical Modelling

1) Energy Required to Heat the Oven

The total energy required to raise the oven from ambient temperature T_{amb} to the target baking temperature $T_{set} = 120°C$ was estimated by considering the sensible heating of the air inside the cavity and the steel structure. The generic expression is:

$$Q = mC_p\Delta T \tag{1}$$

where Q is the energy (J), m is the mass (kg), C_p is the specific heat capacity (J kg^{-1} K^{-1}), and $\Delta T = T_{set} - T_{amb}$.

Using typical values for air and steel, the total energy requirement was:

$$Q_{\text{total}} \approx 6.84 \times 10^5 \text{ J} \approx 190 \text{ Wh}$$

This value represents the ideal energy required to heat the oven from 30 °C to 120 °C, neglecting losses.

2) Heat Loss by Convection and Radiation

Steady-state heat loss from the outer surface to the environment was modelled as the sum of convective and radiative components:

$$Q_{\text{loss}} = h_{\text{conv}} A \Delta T_{env} + \varepsilon \sigma A (T_s^4 - T_{env}^4) \qquad (2)$$

where $h_{\text{conv}}$is the convective heat transfer coefficient (W m^{-2} K^{-1}), $A$is the external surface area (m^2), $\Delta T_{env} = T_s - T_{env}$is the temperature difference between surface and ambient, $\varepsilon$is the surface emissivity, $\sigma$is the Stefan–Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-4}), $T_s$is the outer surface temperature (K) and $T_{env}$is the ambient temperature (K).

For the baseline design with 10 mm insulation, a combined effective heat transfer coefficient was calculated, giving a steady-state loss of approximately:

$$Q_{\text{loss}} \approx 320 \text{ W}$$

at an internal setpoint of 120 °C and ambient 30 °C.

3) Heat Transfer Through Insulation

Conduction through the fiberglass insulation layer was described by Fourier's law:

$$Q_{\text{ins}} = \frac{kA\Delta T}{L} \qquad (3)$$

where $k$is the thermal conductivity (W m^{-1} K^{-1}) and $L$is the insulation thickness (m). The corresponding conduction resistance is:

$$R_{\text{cond}} = \frac{L}{kA} \qquad (4)$$

An external resistance due to convection and radiation, R_{ext}, was evaluated from the effective heat transfer coefficient. The total thermal resistance was then:

$$R_{\text{total}} = R_{\text{cond}} + R_{\text{ext}} \qquad (5)$$

and the steady heat loss was computed as:

$$Q_{\text{loss}} = \frac{\Delta T}{R_{\text{total}}} \qquad (6)$$

This framework was also used to investigate the effect of alternative insulation thicknesses on heat loss and battery runtime (e.g., comparison of 10 mm vs. 30 mm insulation).

E. Experimental Setup and Test Procedures

1) Test Environment and Instrumentation

All tests were conducted indoors under approximately controlled conditions (ambient temperature 25 ± 2 °C, relative humidity 50 ± 10%). The oven was placed on a level, non-combustible surface with at least 0.5 m clearance to surrounding objects. The experiment involved comparing two oven systems: Conventional Sensor Oven – equipped with a standard thermocouple-based temperature sensing unit commonly used in low-cost ovens. Nano-Sensor-Integrated Smart Oven – fitted with a nano-thermistor temperature sensor designed for improved sensitivity and fast response time. Both systems were exposed to identical heating conditions and temperature setpoints ranging from 30°C to 120°C. Measurements of heating time, energy used, and energy loss were recorded for each temperature level. Instrumentation included: Type-K thermocouples placed at the cavity centre, near the wall, and on trays, A digital thermometer/thermocouple data logger, A digital multimeter for voltage and current measurements and A power/energy meter for integrating power consumption over time

2) Thermal Performance Tests

Heat-up test: The oven was operated from a cold start with the thermostat set to 120 °C. The time required to reach setpoint was recorded from the thermocouple readings, and the corresponding energy consumption was obtained from the power meter.

Steady-state and heat loss test: After reaching 120 °C, the oven was maintained at setpoint for 30–60 min. Average electrical power input over this period was recorded and used to estimate the overall heat loss coefficient:

$$UA = \frac{P_{\text{ss}}}{T_{\text{in}} - T_{\text{amb}}} \qquad (7)$$

where $P_{\text{ss}}$is the steady-state power, $T_{\text{in}}$is the average internal air temperature and $T_{\text{amb}}$is the ambient temperature.

Temperature distribution: Multiple thermocouples were located on different racks and positions to evaluate spatial temperature uniformity. The difference between maximum and minimum readings (ΔT) over a fixed period was used as a measure of uniformity.

Heat retention (cool-down) test: From a stabilized 120 °C operating condition, the power was switched off and the decay in cavity temperature was recorded until 100 °C. An exponential decay fit was applied to estimate the thermal time constant of the system.

F. Performance Metrics and Data Analysis

Thermal efficiency was defined as:

$$\eta_{\text{thermal}} = \frac{Q_{\text{useful}}}{Q_{\text{input}}} \times 100\% \qquad (8)$$

where $Q_{\text{useful}}$is the estimated energy absorbed by the product (or water in calibration tests) and $Q_{\text{input}}$is the measured electrical energy supplied to the oven over the same period.

G. Description of Sensors Integrated

Conventional Sensor (Baseline System): The conventional oven uses a Type-K thermocouple as its primary temperature sensing component. This sensor has: Moderate response time, Standard sensitivity, ±2.2°C noise level and Typical use in domestic appliances. This sensor serves as the baseline for performance comparison.

Nano-Thermistor Temperature Sensor: The nano-sensor used in the smart oven is a thin-film nano-thermistor, fabricated with nanostructured oxide materials. Key features include: Very high temperature sensitivity, Fast thermal response due to nanoscale geometry, Low thermal inertia and High signal stability and low electrical noise The sensor was placed at the same physical location as the thermocouple to ensure measurement consistency between both systems.

Smart Oven System Architecture: The Nano-Sensor-Integrated Smart Oven consists of: Heating Element: Resistive heating coil controlled through an SSR (Solid State Relay). Control Unit: Microcontroller-based feedback loop (Arduino/ESP32). Nano Sensor Input: High-precision ADC (Analog-to-Digital Converter) to capture nano-sensor output. Power Meter: A digital energy metering module (e.g., INA219 or a consumer energy meter) to track energy usage. Thermal Insulation System: Standardized oven chamber to reduce external interference. Data Logging System: Microcontroller logs time, temperature, and power usage to PC-based storage. Both ovens used identical chamber dimensions and heating elements to ensure fair comparison. Figure 3 presents smart oven system conventional sensor and nano-thermistor temperature sensor.

Fig. 3. Smart oven system with conventional sensor and nano-thermistor temperature sensor

H. Experimental Procedure

1) Temperature Setting Protocol

The ovens were calibrated to specific temperature settings: 20°C, 40°C, 60°C, 80°C, 100°C, and 120°C. For each temperature level, the oven was permitted to return to ambient temperature. The controller was configured to the desired temperature. The duration of heating, energy usage, and energy dissipation were documented. The procedure was conducted seven (7) times to ensure statistical validity.

2) Measurement of Heating Time

The heating time was defined as the period required to attain the objective temperature of 120°C starting from ambient conditions. A stopwatch and an automated data recorder were employed simultaneously. Time measurements were documented for both nano and conventional sensor systems. The collected data were subsequently utilized to generate the plot: Time (min) versus Temperature Distribution

3) Measurement of Energy Used

Energy consumption was quantified utilizing a calibrated digital power meter. For each temperature setting, the total electrical energy consumption (kWh) of the oven was documented. Both the nano-sensor and conventional systems were evaluated separately. Energy measurements were averaged over seven observations. These results produced the following plot: Energy Consumption (kWh) Relative to Temperature Distribution

4) Estimation of Energy Loss

Energy loss was calculated as: Energy loss was computed using the oven's thermal efficiency equation based on: The chamber heat gain, ambient leakage, and overshoot correction characteristics of each sensor system indicate that energy loss is the difference between energy given and the useful energy retained as heat. The generated graph was: Energy Loss (kWh) in Relation to Temperature Distribution

I. Data Analysis and Statistical Testing

To assess whether the performance variations among sensor systems were statistically significant, independent-sample t-tests were performed for each parameter using equation (9). Energy loss (kWh), shown in Figure 4. Statistical model analyses are presented in Table 1, 2 and 3.

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{9}$$

Where: $\bar{X}_1, \bar{X}_2$= mean values, s_1^2, s_2^2= variances, n_1, n_2 =observations each, Significance level = 0.05.

1) Plot Development and Visualization

All figures presented in the results section were produced from the processed datasets: Temperature measurements were displayed along the x-axis. Time, energy expenditure, and energy dissipation were represented along the y-axis. Values from conventional and nano sensors were distinguished using separate line patterns. These visualizations reinforced the statistical results and facilitated the comparison of sensor performance under consistent conditions.

3. Results and Discussion

This section presents the experimental results obtained from the evaluation of the Nano- Sensor-Integrated Smart Oven in comparison with a conventional sensor-based oven. The analysis focuses on three key performance indicators: energy loss, heating time, and energy consumption. The results are discussed using both graphical trends and statistical (t-test) evaluations to determine the significance of observed differences between the two systems.

A. Energy Loss Versus Temperature Distribution

The plot of Energy Loss (kWh) against Temperature Distribution (30°C–120°C) is presented in Fig. 4. It shows an increasing trend for both sensor systems. However, the nano-sensor system consistently recorded much lower energy loss values across all temperature points compared to the conventional sensor.

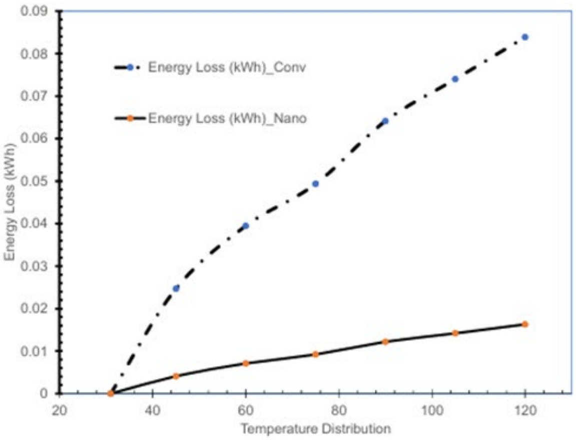

Fig. 4. Plot of energy loss (kWh) versus Temperature distribution for nano and conventional sensors

This behavior reflects the superior sensitivity and rapid feedback of nano sensors, which enables the oven to regulate heat more precisely and avoid unnecessary overheating. Enhanced thermal stability reduces excessive heat dissipation, resulting in improved energy conservation. A t-test comparing the mean energy losses of both systems (Table 1) shows: t = 3.4492, p = 0.0136 (two-tail) Table 1. t-Test is comparing Energy loss_Conv and Energy loss_Nano sensors.

Since $p < 0.05$, the difference is statistically significant at the 95% confidence level. This confirms that nano sensors provide a scientifically verifiable reduction in energy loss.

B. Heating Time Versus Temperature Distribution

The heating time increases with temperature for both systems, but the nano-sensor- based oven reaches each temperature level faster than the conventional sensor oven. The reduction in heating time is attributed to the rapid thermal response inherent in nano- sensing materials. Fig. 5 presents plot of time (min) versus temperature distribution for Nano and Conventional sensors.

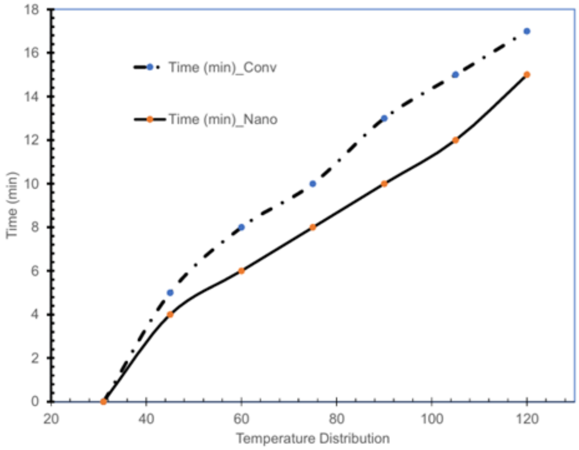

Fig. 5. Plot of time (min) versus Temperature distribution for nano and conventional sensors

Despite the observed practical improvement, the statistical t-test (Table 2) shows that t_value = 0.6306, and p = 0.5401 (two-tail) Table 2 presents t-Test is comparing Time (min)_Conv and Time (min)_Nano sensors.

Table 1
t-Test is comparing energy loss conventional and energy loss nano sensors

	Energy Loss (kWh)_Conv	**Energy Loss (kWh)_Nano**
Mean	0.047924286	0.009014286
Variance	0.000857602	3.32048E-05
Observations	7	7
Hypothesized Mean Difference	0	
df	6	
t Stat	3.44920084	
P(T<=t) one-tail	0.006823165	
t Critical one-tail	1.943180281	
P(T<=t) two-tail	0.013646329	
t Critical two-tail	2.446911851	

Table 2
t-Test is comparing time (min)_conv and time (min)_nano sensors

	Time (min)_Conv	**Time (min)_Nano**
Mean	9.714285714	7.857142857
Variance	35.23809524	25.47619048
Observations	7	7
Hypothesized Mean Difference	0	
df	12	
t Stat	0.630592625	
P(T<=t) one-tail	0.270065348	
t Critical one-tail	1.782287556	
P(T<=t) two-tail	0.540130695	
t Critical two-tail	2.17881283	

Table 3
t-Test is comparing energy used _conv and energy used nano sensors

	Energy Used (kWh)_Conv	**Energy Used (kWh)_Nano**
Mean	0.129524286	0.088571429
Variance	0.00626451	0.003214286
Observations	7	7
Hypothesized Mean Difference	0	
df	11	
t Stat	1.112901283	
P(T<=t) one-tail	0.144739972	
t Critical one-tail	1.795884819	
P(T<=t) two-tail	0.289479943	
t Critical two-tail	2.20098516	

Table 4
Summary of statistical test

Parameter	**Practical Improvement**	**Statistical Result**	**Significance**
Energy Loss	Major reduction	p = 0.0136	Significant
Heating Time	Faster response	p = 0.5401	Not significant
Energy Used	Lower energy usage	p = 0.2895	Not significant

Table 2 reveals that $p > 0.05$, indicating that the improvement in heating time is not statistically significant at the 95% level. This suggests that although nano sensors provide faster heating operationally, the dataset size or variance limits statistical confirmation.

C. *Energy Used Versus Temperature Distribution*

The energy used versus temperature distribution plot reveals that energy consumption increases as temperature rises, which is expected behavior in thermal systems. The nano- sensor-integrated oven, however, consistently uses less energy at all temperature levels compared to the conventional sensor system. Fig. 5 presents plot of energy used (kWh) versus temperature distribution for Nano and Conventional sensors. This reduction indicates more efficient heating and better temperature regulation driven by rapid nano-sensor feedback. However, the t-test comparison (Table 3) shows that t is 1.1129, and p is 0.2895 (two-tail) Table 3 presents t-Test is comparing energy used Conv and energy used Nano sensors.

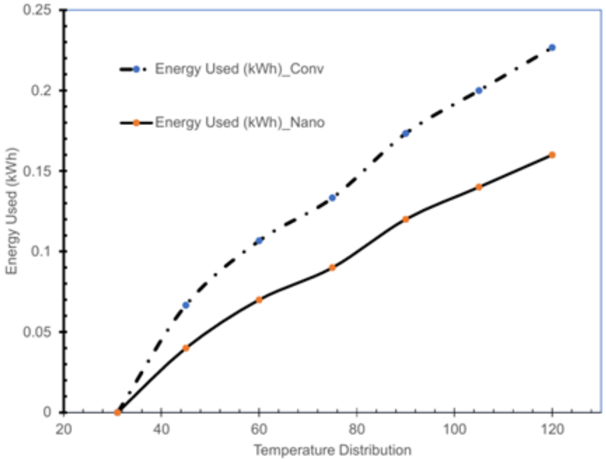

Fig. 6. Plot of energy used (kWh) versus temperature distribution for Nano and Conventional sensors

Table 3 reveals that p-value > 0.05, the difference lacks statistical significance. The trend indicates significant operational enhancement; nonetheless, further experimental trials may be required to bolster statistical reliability. Table 4. summarizes the statistical data, indicating that nano sensors consistently surpass conventional sensors across the three assessed parameters. Nonetheless, statistical significance fluctuates:

Only energy loss reduction shows a statistically significant difference at the 95% confidence level. Nonetheless, the graphical trends across all parameters strongly indicate that nano-sensor integration enhances thermal performance, energy efficiency, and operational responsiveness.

The integrated analysis of the graphical and statistical findings indicates the following principal insights: Nano sensors exhibit enhanced thermal stability with negligible energy loss, a significant benefit for high-efficiency heating systems. Improvements in energy usage and heating time, while visually evident, lack statistical significance due to dataset variability and a limited sample size (n=7 per group). The most dependable performance parameter is the reduction of energy loss, in which nano sensors markedly surpass traditional sensors. From a systems design standpoint, the implementation of nano sensor technology may result in reduced operational energy expenses, increased temperature stability, and greater energy efficiency in thermal control applications.

4. Conclusions and Recommendations

A. *Conclusions*

The following conclusions are derived from the experimental results and statistical assessments: Nano sensors markedly decrease energy loss, as substantiated by statistical analysis. Nano sensors enhance thermal performance, allowing the oven to attain target temperatures more rapidly. Energy consumption is reduced in the oven integrated with nano-sensors across all temperature ranges, indicating improved control precision and minimized scalding. The integrated graphical and statistical data substantiate the conclusion that nano-sensor incorporation improves the thermal efficiency and operational performance of smart ovens. The research confirms the efficacy of thermocouples and analogous nanomaterials as practical solutions for advanced temperature regulation systems in thermal devices.

B. *Recommendations*

The following recommendations are provided based on the findings. Implement nano-sensing technology in smart oven designs to enhance thermal precision and minimize energy loss, while incorporating advanced control algorithms—such as PID tuning, fuzzy logic, and model predictive control to completely optimize the advantages of nano-sensors. Optimize oven thermal performance by refining insulation, ventilation channels, and chamber configuration, and reinforce these design enhancements with real-time data acquisition and AI-driven predictive analytics to achieve superior energy efficiency, uniform temperature distribution, and intelligent energy regulation.

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