Journal of Sustainable Engineering & Renewable Energy (JSERE)

VOLUME 1 ISSUE 1 (2025)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

Journal of Sustainable Engineering & Renewable Energy (JSERE)

Volume 1 Issue 1, Year 2025
https://journals.e-palli.com/home/index.php/jsere

Optimizing Agricultural Drying Technologies: A Systematic Review of Charcoal, Gas, and Hybrid Kilns for Sustainable Food Preservation

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Article Information

Received: April 12, 2025

Accepted: May 15, 2025

Published: June 30, 2025

Keywords

Charcoal Kilns, Drying Rate, Drying Technologies, Economic Viability, Emissions, Energy Efficiency, Gas-Fired Kilns, Sustainable Agriculture, Thermal Efficiency

ABSTRACT

In global agriculture, post-harvest losses continue to be a major problem, especially in developing nations where insufficient drying technologies lead to significant food waste. This study systematically evaluates the performance of charcoal and gas drying kilns, focusing on efficiency, cost, and operational flexibility. Boolean search techniques were used to examine drying technologies in a thorough evaluation of peer-reviewed research using databases such as IEEE Xplore, ScienceDirect, and Scopus. The results show that, although they are inexpensive and widely available, charcoal kilns have inconsistent heat output, high emissions (1671g CO_2/kg charcoal), and deforestation risks. In contrast, gas-fired kilns exhibit superior temperature control, energy efficiency (up to 70.9% exergy efficiency), and lower emissions, but they also require a higher initial investment. A balanced solution for environments with limited resources was provided by hybrid systems that combined gas and charcoal technologies to save drying times by 50% without sacrificing product quality. The study emphasizes trade-offs: gas kilns are cleaner but more difficult to reach, whereas charcoal kilns are more expensive but environmentally unsustainable. A promising substitute that can be adjusted to the fuel supply is a hybrid system. Scaling hybrid technology, implementing regulatory incentives to encourage the use of cleaner energy, and conducting additional research on the integration of renewable energy sources are among the recommendations. This evaluation helps engineers and farmers choose the best drying options to improve sustainability and food security.

INTRODUCTION

Post-harvest losses continue to be a serious concern for global agriculture, particularly in underdeveloped countries where storage and preservation infrastructure are frequently inadequate (Kaur & Watson, 2024; Kiaya, 2014; Kumar & Kalita, 2017). According to estimates, post-harvest losses can account for up to 40-50% of total agricultural production in some locations, with drying and storage being key points of loss (Kiaya, 2014).

In Nigeria, drying has been the primary technique for preserving agricultural food products since it is easy to use, requires little energy, and is seasonal in food production but year-round in consumption (Issa *et al.,* 2020). The essence of drying various food products is to reduce moisture level, weight, and make handling easier; to prolong shelf life; to preserve nutritional quality of food; and reduce risk of contamination by toxic molds, etc. (Tawari, 2006). Traditional drying methodologies, such as solar drying and atmospheric drying, frequently result in inadequacies, including heterogeneous moisture allocation and elevated energy expenditure, which may jeopardize the integrity of the product (Khaing Hnin *et al.,* 2019). Moreover, traditional drying practices have relied on environmental air or natural solar radiation, which can be unpredictable and inadequate depending on the geographical context (Mujumdar, 2006). Drying kilns were created in response to these constraints to provide controlled environments that aid in the drying process by lowering the moisture content of materials through the application of controlled heat and airflow (Keey, 2013; Nikolopoulos *et al.,* 2015).

An environmentally friendly option for drying applications is to include a hybrid energy system that uses both gas and charcoal. In drying kilns, wood and charcoal have traditionally been the primary fuels due to their affordability and ease of availability. A renewable resource, charcoal is created by pyrolysing organic materials (Demirbas *et al.,* 2016). It is a dominant source of energy in most developing nations like Nigeria, characterized by a high calorific value of about 29600kJ/kg and a tendency to conserve heat (Nwakuba, 2016), which could be highly promising and also an alternative source of energy for drying. It has fewer emissions and a high thermal efficiency when compared to fossil fuels (Demirbas *et al.,* 2016). However, these fuels have a lot of drawbacks, such as inconsistent heat output, deforestation, and air pollution. As a result, alternative energy sources such as gas (natural gas, liquefied petroleum gas, etc.) have become increasingly popular due to their cleaner burning and more controlled heating characteristics (Mahapatra *et al.,* 2021; Moka *et al.,* 2014; Montazerinejad & Eicker, 2022). Gas-fueled kilns allow accurate temperature control, which is crucial for the consistent drying of food goods. Gas can be costly and not always easily accessible, especially in rural or isolated places. (Economides & Wood, 2009). However, the environmental implications of gas usage, particularly in terms of greenhouse gas emissions, necessitate careful

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management and innovation in kiln design (Napp *et al.,* 2014). Although it is more widely available and offers a consistent source of heat, charcoal is less effective and more harmful to the environment than gas (Gaffney & Marley, 2009). An important advancement in the realm of food drying is the creation of dual-energy kilns, which can run on both gas and charcoal. These kilns allow the option to switch between energy sources based on availability, cost, and environmental considerations. This adaptability is particularly useful in areas where, depending on the season or the situation, one fuel source may be more dependable or economical than the other (Nnabuife *et al.,* 2024).

This paper is structured to provide a systematic review of charcoal (Okpala *et al.,* 2025; Onyenanu *et al.,* 2024) and gas drying kilns, beginning with their technical mechanisms, followed by comparative performance measurements, economic assessments, and real-world case studies (Kshirsagar & Kalamkar, 2014). This review attempts to assist farmers, policymakers, and agricultural engineers in choosing the best drying solutions based on their unique requirements, available resources, and long-term sustainability objectives by assessing these technologies from both small- and large-scale perspectives. In order to reduce post-harvest losses and improve food security, the objective is to support well-informed decision-making that strikes a balance between sustainability, cost, and efficiency.

LITERATURE REVIEW

Post-harvest losses are still a major problem in agriculture worldwide, especially in developing nations where a lack of proper drying facilities leads to a large amount of food waste (Kumar & Kalita, 2017). Uneven moisture distribution and product deterioration are frequent outcomes of conventional drying techniques such as outdoor sun drying (Mujumdar, 2006). Modern drying kilns have been created to overcome these constraints, and gas-fired and charcoal-fired systems have emerged as popular options. Due to their high calorific value and affordability, charcoal kilns are frequently used; yet, they have drawbacks, including uneven heat output and environmental issues (Demirbas *et al.,* 2016). However, because of their greater prices and infrastructure needs, gas-fired kilns are frequently less accessible in rural regions, despite their superior temperature control and reduced emissions (Akhtar *et al.,* 2015). The goal of recent developments, such as hybrid drying systems, is to mitigate the drawbacks of both technologies while combining their advantages (Nwakuba *et al.,* 2018). Later sections of this study will provide a more thorough and methodical analysis of these technologies, covering their sustainability implications, economic viability, and performance indicators.

MATERIALS & METHODS

With an emphasis on assessing their mechanical performance, financial implications, operational flexibility, and thermal efficiency, this study carried out a thorough analysis of drying technologies that are fuelled by gas and charcoal and utilised in agricultural applications. Finding performance patterns, technological gaps, and the relative advantages of using gas and charcoal as drying kiln heat sources were the goals of the review. Drying rate, energy utilisation, greenhouse gas emissions, product quality retention, and fuel interchangeability were important factors considered.

Data Collection and Selection

The literature was mainly sourced from peer-reviewed databases such as Scopus, ScienceDirect, MDPI, SpringerLink, IEEE Xplore, and Google Scholar, which were selected because of their extensive index of publications in agricultural engineering, renewable energy, thermal sciences, and post-harvest technology. This ensured academic rigour and coverage of both

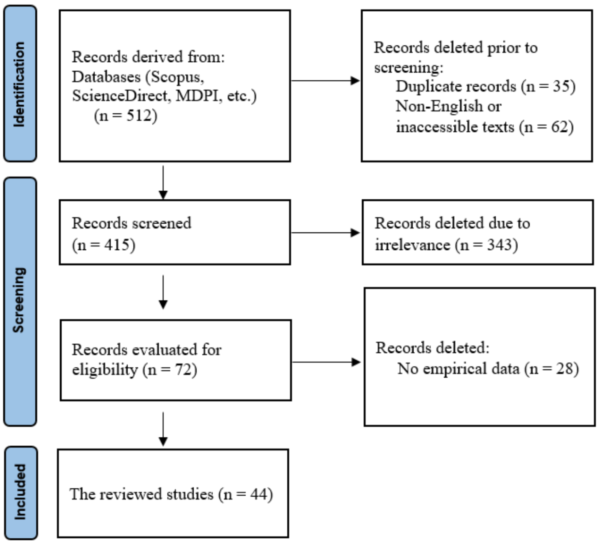

Figure 1: PRISMA Flow Diagram for the Process of Literature Selection
Source: Page et al. (2021)

engineering and agricultural research.

A Boolean search strategy was developed to capture relevant studies on charcoal and gas-powered drying systems:

- ("charcoal drying kiln" OR "charcoal-fired dryer" OR "biomass kiln")
- AND ("gas drying kiln" OR "LPG-fired dryer" OR "natural gas kiln")
- AND ("drying efficiency" OR "thermal performance" OR "drying rate")
- AND ("agriculture" OR "food drying" OR "post-harvest technology")

The search period, which spanned from 2000 to 2024, covered 20 years of advancements in post-harvest engineering, energy use, and dryer design. 512 articles were returned by the original query. Forty-four (44) papers were chosen for a thorough assessment after being screened for language (English), duplication, relevance, and publishing quality (peer-reviewed journals and conferences).

Publication of Journals by Ranking

As seen by the publication patterns in Figure 2, research interest in charcoal and gas drying technologies for agricultural applications has grown significantly in recent years, with a pronounced concentration of studies emerging in the current decade. According to the data, there is a strong academic focus on thermal efficiency, drying rate, emissions reduction, etc; 36.4% of the evaluated publications (16 out of 44 studies) were published between 2020 and 2023 alone. This surge in research production is a reflection of how crucial sustainable post-harvest solutions are becoming. A prime example of how technological innovation is tackling efficiency and sustainability issues in agricultural processing, especially in developing regions where post-harvest losses continue to be a significant problem, is the creation of hybrid drying systems that combine the affordability of charcoal with the cleaner combustion of gas.

Figure 2: Graph of Journal Article by Year of Publication (Osobajo *et al.,* 2017)

Reviews

Critical information about the effectiveness, economic feasibility, and environmental impact of gas drying and charcoal technologies can be found through a systematic review; recent research shows a clear trend towards hybrid and energy-efficient solutions.

Classification of Drying Methods

Drying technologies are categorised methodically in Table 1, which also compares their typical uses, performance results, and operating principles. This overview demonstrates how solar, vacuum, and hybrid technologies each address specific moisture-removal difficulties, allowing practitioners to select appropriate options based on crop variety, energy availability, and quality needs.

Table 1: Classification of Drying Methods with Supporting Literature

Study Topic	Drying Method	Principle	Typical Applications	Findings	Citations
"Study the drying kinetics of open sun drying of fish."	Sun Drying (open/active)	"…carried out by tradition under the open sun"	Fish, fruits, vegetables, grains, etc	"The average effective moisture diffusivities were 11.11 · 10 11 and 8.708 · 10 11 m^2 s 1 for prawn and chelwa fish drying, respectively."	Jain & Pathare (2007)

"Recent developments in greenhouse solar drying: A review"	Solar Drying (passive)	"… Solar dryer is based on the principle of the greenhouse effect. It allows incoming short-wavelength solar radiation from the sun and traps the long-wavelength solar radiation. "	"It is used for crop cultivation, poultry, aquaculture, soil solarisation, and crop drying."	"It is suitable for high moisture content crops. Color, quality, taste, and nutritional value of the dried product are better in greenhouse solar drying than open sun drying."	Singh *et al.* (2018)
"Vacuum drying and hybrid technologies"	Vacuum Drying	"The processes of vacuum drying can be considered according to the physical conditions used to add heat and remove water vapour."	"Ideal for materials that can be damaged or changed if exposed to high temperatures."	"As a result, combined vacuum drying systems have a good potential to increase effectiveness, quality, and energy efficiency."	Bezyma & Kutovoy, (2005)
"Freeze drying process: a review"	Freeze Drying	"The fundamental principle in freeze-drying is sublimation, the shift from a solid directly into a gas."	"Mainly used for the drying of thermo-labile materials."	"So, all-over freeze drying is a very effective and necessary technology from a pharmaceutical point of view."	Shukla (2011)
"Drum Drying"	Drum Drying	"Here, liquid, slurry, or puree material is applied as a thin layer onto the outer surface of revolving drums that are internally heated by steam.".	"High viscous liquid or pureed foods"	"Drum drying is one of the most energy-efficient	Tang *et al.* (2003)
"Spray Drying: An Overview"	Spray Drying	"Spray-drying mechanism is based on moisture elimination using a heated atmosphere to which the feed product is subjected."	Milk powder, coffee, flavorings	"The scalability of this manufacturing process in obtaining dried particles in submicron-to-micron scale favors a variety of applications within the food, chemical, polymeric, pharmaceutical, biotechnology, and medical industries."	Santos *et al.*, (2018)

"Microwave drying of fruits and vegetables"	Microwave Drying	"In microwave drying, when the material couples with micro wave energy, heat is generated within the product through molecular excitation."	Vegetables, herbs, quick-dry foods	"The benefit of using a microwave lies in its short processing time, which is most advantageous for product quality when compared with other drying techniques."	Changrue *et al.,* (2006)
"Infrared Heating in Food Drying: An Overview"	Infrared Drying	"By subjecting the material to infrared radiation, the heating power generated can penetrate into the food materials."	Vegetables, fruits, thin slices, grains	"Using infrared heating for food drying purposes has become more popular in the last decade, and its application in the industrial drying of different foodstuffs has been employed widely."	Riadh *et al.,* (2015)
"Fluidized bed drying of some agro products – A review"	Fluidized Bed Drying	"It increases the efficiency of these processes by enabling the entire surface of the product to behave like molten lava and mixing solid materials efficiently with the drying air."	Drying agricultural products	"Higher throughput with better quality for a range of products (having different shape, bulk density, physical and chemical properties) can be achieved in FBD drying…"	Sivakumar *et al.,* (2016)
"Recent developments in radio frequency drying of food and agricultural products: A review"	Radio Frequency Drying	"It is a volumetric heating method where electromagnetic waves directly couple with food to generate heat."	Bulk agricultural produce	"Radio Frequency-related combination drying takes advantage of both conventional drying methods and RF heating, leading to improved drying uniformity, better product quality, and higher energy efficiency."	Zhou & Wang, (2019)

Energy Source, Efficiency, and Applications in Drying Kilns

Thermal efficiency, drying rates, and operating costs are among the important indicators that are systematically compared among energy sources in Table 2. This summary shows how fuel choice has a direct effect on environmental sustainability and economic feasibility.

Table 2: Classification of Energy Sources used by kilns showing their performance metrics

Energy Source	**Study Topic**	**Key findings/Performance metrics**	**Significance of Study**	**Citations**
Charcoal	"Design, Fabrication and Performance Evaluation of a Charcoal-Fired Tomato Dehydrator for Developing Countries"	"The results of its performance evaluation showed that, with a safe drying air temperature of 50 °C at 6 m/s fan speed, the dehydrator is capable of drying 5 kg of tomatoes per batch from an initial moisture content of 94% to 22% with a final weight of 1.4 kg over a drying period of about 7 hours. The microbiological analysis conducted on the post-drying tomato sample revealed a total bacterial count (TBC) of 1.61 x 10^2 cfu/g and a total fungus count (TFC) of 0.27 x 10^2 cfu/g, which are both far below the allowable limits (10^3 cfu/g) for human consumption. "	"The dehydrator has proved effective for extending the shelf life of tomatoes by mitigating the rate of spoilage due to microbial activities through drying, thereby enhancing the food security and economy of developing countries."	Oluleye (2019)
	"Performance evaluation of a developed fish smoking kiln in Benue state, Nigeria"	"Reduced the moisture content leading to reduced weight of fish from 337.4g to 167.6g within 14.44hrs."	"The kiln is capable of improving the quality of fish, reducing the drudgery associated with traditional fish drying methods, and consequently reducing post-harvest losses."	Agim *et al.* (2023)
	"Design and Fabrication of a Charcoal Fish Smoking Kiln"	"…cat and panla smoked to an average moisture content of 62.5% within an average period of 4 hours, the average final weight of the dried fish was 0.24 Kg, weight loss 22.45Wb, residence temperature of 60-80 °C, heat exchanger temperature is 243 °C, and heat different at chimney 242 °C.	"The fabricated machine is highly efficient. It produced dried smoked fish that lasted for seven weeks without spoilage."	Issa *et al.,* (2020)
	"Performance of Smokehouse Designed for Smoking Fish with the Indirect Method"	"The results showed that the smoking system was able to complete the smoking process of the fish in 13 h with 20.1% moisture reduction."	"Based on the test results, the indirect smoking system developed and tested in this study was shown to be able to perform the smoking fish process satisfactorily and produce clean smoked fish."	Sintali *et al.,* (2023)
	"Design and evaluation of a small-scale processing charcoal kiln"	"The time required, quantity of the biomass, and temperature were factors taken into consideration during the carbonization process. At 90mins, 10kg of oil palm kernel shells carbonized at 629°C and yielded 2.738kg of charcoal."	"This project was able to construct a carbonization kiln using a metal drum, which was successfully used for the carbonization of the precursor materials (coconut shells and palm kernel shells) to produce charcoal/carbon."	Gold *et al.* (2024)

	"Drying kinetics of olive pomace-derived charcoal briquettes with energy consumption"	"The results were in the range of 3 to 8 hours of drying time. The max–min percentages of consumed thermal and mechanical energies in the drying process of the olive pomace briquette were 92.09 and 7.09%, respectively."	"The results of the energy analysis indicated that drying olive pomace briquettes at higher temperatures, lower velocities, and a lower relative humidity of drying air had better energy efficiency."	Say *et al.* (2022)
	"Performance Evaluation of a Fabricated Smoking Kiln"	"Heat capacity, thermal resistance, and heat requirement of the machine were found to be 2337.57 kW, 2.16 K/W, and 1123.20 kJ (fish); 1000.35 kJ (beef); 1584.24 kJ (chicken), respectively."	"The machine is effective, user-friendly, hygienic, free no health risk to processors, and improves product quality."	Jimoh & Oni (2022)
Solar	"Design, construction, and evaluation of a mixed-mode solar kiln with black-painted pebble bed for timber seasoning in a tropical setting"	"Kiln drying reduced timber moisture content from 66.27% to 12.9%, whereas open air drying reduced it to 20.1% dry basis in 360 hours. Also, the initial drying rates for both kiln-dried wood and control were 0.205% and 0.564% per day, and the final drying rates were 0.15% and 0.08% per day, respectively."	"The rapid rate of drying in the kiln reveals its ability to dry timber to a safe moisture level without defects."	Ugwu *et al.* (2015)
	"A greenhouse-type solar dryer for small-scale dried food industries: Development and dissemination"	"Results obtained from these experiments showed that drying air temperatures in the dryer varied from 35°C to 65°C. In addition, the drying time for these products was 2-3 days shorter than that of the natural sun drying, and good quality dried products were obtained."	"Due to its technical and economic effectiveness, this type of solar dryer has been officially included in the dissemination program by the Department of Alternative Energy Development and Efficiency of Thailand."	Janjai (2012)
	"Solar-assisted drying of timber at industrial scale"	"The investigations showed that investments, drying costs, and energy consumption could be reduced by 50 % compared to conventional high-temperature drying systems. At the same time, the quality of the timber was improved considerably."	"It allows a controlled drying of up to $250m^3$ of timber per load."	Bux *et al.* (2001)
Agricultural waste (sawdust, palm kernel shell, and rice bran)	"Fish Smoking Kiln Using Agricultural Wastes as Energy Source"	"Calculation further showed that the kiln has 69.4% energy efficiency and drying period of 10 hours at an average temperature range of 60 – 120 °C, depending on the type of agricultural waste used as a source of fuel energy. Also determined were the fuel conversion ratio, drying rates, and calorific values of the different agricultural waste products. Calorific value of the four agricultural wastes ranged between 16.2 MJ/Kg in palm kernel to 30 MJ/Kg in charcoal."	"It is used as an alternative to the usual conventionally used conventional charcoal as an energy source for smoking fish."	Daramola *et al.* (2020)

Gas	“Efficient energy-saving gas tunnel kiln”	“Compared with an original tunnel kiln, the efficient energy-saving gas tunnel kiln saves energy by 29.3 percent, facilitates controlling the firing cost of an enterprise within the range below 30 percent, and greatly improves the energy utilization rate.”	“Efficient energy-saving gas tunnel kiln is beneficial for improving firing qualified rate and firing quality of the product.”	Junping *et al.,* 2013)
	“Exergetic Evaluation of a Biomass Gasifier Operated Reversible Flatbed Dryer for Paddy Drying in Parboiling Process”	“The exergy efficiency is found to be 70.929% for the gasifier, 62.411% for the scrubber, 35.288% for HAG, 11.30-76.65% for the drying cabinet with an average value of 34.81%, and 5.267-14.44% for the overall drying system. The average exergy efficiency of the overall drying system is found as 21.28% respectively.”	“Useful for the researchers and designers of the drying system.”	Wincy *et al.* (2023)
	“Evaluating the combustion process of a methane-fired cross-draft ceramic kiln for efficiency and sustainability”	“The results also showed that enthalpies of formation of products and reactants of -74,897 and -557,376.843 were generated at an air-methane equivalent ratio of 1:5 and a stoichiometric ratio of 9.818. This translates to 57.18% of air available for the combustion process and a 42.82% deficiency.”	“The study concluded that though the combustion process of the methane-fired kiln was weak, resulting in thermal energy loss of 39.9%, there was an energy utilization of up to 60.1%.”	Abubakar *et al.,* (2023)
Biogas	“Evaluation of biogas calorific potential for use in medicinal plant dryers”	“The burning of biogas generated 36.10 MJ h^{-1}, 68.95 MJ h^{-1} and 76.03 MJ h^{-1} for treatments T1, T2 and T3, respectively, meeting the need for heating in the drying chamber operating at temperatures of 43.05 °C (T1), 52.56 °C (T2) and 53.56 °C (T3).”	“The heating system proposed has proved to be effective for drying different species of medicinal plants, since it meets the temperature range specified in the literature.”	Corrêia *et al.,* (2016)
Biomass	“Development of a Cross-Flow Fish Smoking Kiln Fired by Biomass Material”	“The temperature of the chamber increased to about 120 °C to 160 °C when fueled with sawdust and about 150 °C to 200 °C for maize cob. The total heat transfer resistance through the kiln walls was determined to be 1.0 °C/W. About 4 to 6 hours was required to smoke-dry 16 kg of fish samples from the initial moisture content of 70% to about 20% or 35% moisture level.”	“The fish smoking kiln designed and fabricated in this study addresses these problems (inconsistently smoked fish).”	Oyerinde *et al.,* (2012)

Hybrid Drying Systems: Fuel Combinations and Operational Outcomes

Recent improvements in hybrid drying technologies have revealed new opportunities for adaptable, sustainable post-harvest processing. Table 3 investigates innovative fuel integration solutions and their demonstrable implications on drying efficiency, product quality, and environmental footprint across varied agricultural applications.

Table 3: Classification of Energy Sources used by kilns showing their performance metrics

Study Topic	**Energy Source**	**Key findings/Performance metrics**	**Significance of Study**	**Citations**
"Thin-layer drying kinetics of fish in a hybrid solar-charcoal dryer"	Solar and charcoal	"The times required to reduce 50% initial moisture content (wet basis) of Titus fish species (75.24%wb) were 90,120, and 160 minutes at fillet thicknesses of 3, 5, and 7mm respectively; whilst that of sardine (79.61%wb) was 60, 75, and 110 minutes of fillet thicknesses of 3, 5, and 7mm respectively. The maximum and minimum times required to smoke dry Titus and sardine fish samples at varying fillet thicknesses were 4½ to 7 hours and 4 to 6½ hours, respectively."	"Presented an empirical thin-layer model describing the drying kinetics of Titus and sardine fish samples using an indirect passive hybrid solar-charcoal smoke dryer."	Nwakuba *et al.,* (2018)
"Impact of Improved Smoking Kiln Design on Hygiene and Timeliness of Drying of Smoked Fish"	Charcoal and gas	"The MC d.b. values of smoked fish when the suction blower was used with charcoal and gas for 4 4-hour duration were 10.45% and 11.76%, respectively. Without the blower, the values were 14.3% and 11.70%, respectively. The processed smoked fish produced was hygienic."	"Hygienic processing and practices of smoked fish and products can ensure food safety in our society."	Okusanya *et al.,* (2021)
"Development of a Dual-Powered Fish Smoking Kiln"	Charcoal and electric heat sources	"The kiln gave a higher drying rate and required more energy cost for all three fish types when powered with charcoal. However, it was discovered that the labour cost of using charcoal was less than that of the electric heat source. However, it was discovered that the labour cost in using charcoal is less than that of the electric heat source."	"The kiln gave a higher drying rate and required more energy cost for all three fish types when powered with charcoal."	Ajewole *et al.,* (2021)
"Comparison of Energy Consumption of Cereal Grain Dryer Powered by LPG and Hard Coal in Polish Conditions"	LPG and hard coal	"According to the approach presented in this paper, the S428. CS construction powered by LPG gas had an energy consumption that was 6.14% lower than the DT2532 dryer construction, which used hard coal."	"It could be useful for manufacturers who could use this method to generate more reliable data in their product datasheets, and it could also be legally regulated as an appropriate tool for calculating the energy consumption of agricultural grain dryers."	Debowski *et al.,* (2021)
"Performance of a large-scale greenhouse solar dryer integrated with phase change material thermal storage system for drying of chili"	Solar integrated with a PCM as a latent heat storage	"The exergy efficiency of the drying room of the solar dryer integrated with the PCM thermal storage and the solar dryer without the PCM thermal storage for drying of chili was found to be 13.1% and 11.4%, respectively, and the thermal storage helps to dry chili during adverse weather conditions."	"The results of exergy analysis implied that the exergy losses from the dryer with the PCM should be reduced."	Pankaew *et al.,* (2020)

"Evaluation of Technology Transfer to Rural Communities for Drying Using LNG and Solar Energy Cabinet Dryer"	LPG and solar energy.	"The results are as follows: the consumption of the liquefied petroleum gas (LPG) was 2.10±0.11 kg, the electrical power for the blower was 21.3±3.2 W, the average drying rate was 0.54±0.10 kgwater/h, and the average energy consumption was 11.08±1.40MJ/kgwater."	"The findings will be useful in the development of the well-being of the people in the community for a better lifestyle. Two dryers were installed at Doi Sarm Muan and Namru villages in the Chiang Mai province. The results of the present work were very well received."	Achariyaviriya *et al*., 2014)
"Performance Characterization of a Locally Developed Fish Smoke-Drying Kiln for Charcoal and Briquette"	Charcoal and briquette	"Results showed that the energy efficiency of the kiln was 97.02% and 98.45%, and specific fuel consumption was 2.57 and 4.20 for charcoal and briquette, respectively. The energy expended by charcoal and briquette fuel materials was 206 MJ and 249.6 MJ, respectively. The energy expended, energy efficiency, and specific fuel consumption were higher for briquette than for charcoal. The use of charcoal offered higher moisture removal and drying rate for the smoke-drying process than briquette, but no significant difference was observed."	"Economically, briquette compares closely with charcoal, and could be considered a good alternative fuel material for smoke-drying of fish."	Amponsah *et al*., (2022)
"Fabrication and Performance Evaluation of a Hybrid Fish Smoking Kiln"	"Propane gas and three biomasses, namely: iron tree, rice husk, and sawdust."	"The phenol and protein contents of smoked fish ranged between 0.14 and 0.18 g/cm3 and 66.45–67.14%, respectively."	"The study has revealed innovative means of smoking fish for efficiency, quality, and profitability in terms of reduction in the cost of production (low wood consumption, smoke dusting, and drying rate)."	Alakali *et al.,* (2017)

Key Differences Between Charcoal and Gas Drying Technologies

The decision between charcoal and gas-fired drying technologies entails important trade-offs on operational, environmental, and economic levels. This is illustrated in Table 4.

Table 4: Performance Trade-offs Between Charcoal and Gas Drying Technologies

Aspect	**Charcoal Kilns**	**Gas-Fired Kilns**
Greenhouse Gas Emissions	Charcoal manufacture and consumption emit significant amounts of greenhouse gases (GHGs). Incomplete combustion in traditional kilns can lead to substantial emissions of CO_2, CH_4, and CO. According to Belay *et al.* (2024), "1671 g of carbon released per kg of charcoal" is produced in the Awi zone. Their findings also show that the average primary global warming impact (PGWI) for the 18 sample kilns was 7.6 kg CO2-eq per kg charcoal produced.	Gas-fired kilns generally produce fewer greenhouse gas emissions. Natural gas combustion emits primarily CO_2 and water vapor, with lower levels of CH_4 and CO (Semin, 2008) compared to charcoal combustion. This leads to a reduced total GWC, making gas-fired kilns a cleaner option.

Operational Costs	While the initial investment for traditional charcoal kilns is generally inexpensive, the operational costs can be substantial due to low efficiency and the labor-intensive nature of charcoal manufacturing (Onyenanu *et al.,* 2023; Sparrevik *et al.,* 2015). Additionally, the environmental consequences of deforestation and emissions are enormous.	For infrastructure and equipment, gas-fired kilns can require a larger upfront capital expenditure (Gomes & Hossain, 2003). However, over time, its cleaner combustion and increased efficiency may result in cheaper operating costs (Akhtar *et al.,* 2015; Schütt, 2023a).
Sustainability	To produce charcoal, wood must frequently be harvested in an unsustainable manner, which results in habitat loss and deforestation (Chidumayo & Gumbo, 2013; Rotowa *et al.,* 2019). These problems are made worse by the inefficiency of conventional kilns, which need more wood to create the same quantity of charcoal (Tazebew *et al.,* 2023).	Gas-fired kilns are a more environmentally friendly choice, particularly if the gas comes from cleaner fossil fuels or renewable resources (Akhtar *et al.,* 2015). Because of their increased efficiency, less fuel is used overall, and their lower emissions help to lessen their environmental impact (Akhtar *et al.,* 2015).

Discussion

Performance Evaluation of Charcoal and Gas Drying Technologies

The effectiveness and drying capabilities of gas-fired kilns and charcoal are important considerations when assessing their viability for use in agriculture. Charcoal kilns are a popular option in developing nations like Nigeria because of their high calorific values (~29,600 kJ/kg) and efficient heat retention (Nwakuba, 2016). For example, in 7 hours at 50°C, a tomato dehydrator powered by charcoal reduced moisture content by 94% to 22%, as shown by Oluleye (2019). However, conventional charcoal kilns frequently need a lot of fuel to maintain temperatures due to their uneven heat output and poor combustion efficiency (Demirbas *et al.,* 2016). In contrast, gas-fired kilns display improved temperature control, with natural gas systems reducing energy usage by 29.3% compared to conventional designs (Junping *et al.,* 2013). The exergy efficiency of gasifier-based drying systems reaches 70.9%, highlighting their potential for optimized energy use (Wincy *et al.,* 2023). As demonstrated by smoking fish, where the moisture content was lowered from 70% to 20% in just 14.44 hours, charcoal kilns are capable of quickly removing moisture (Agim *et al.,* 2023). However, if temperatures change, uneven heating can degrade product quality and result in microbial contamination (Issa *et al.,* 2020). This is addressed by gas kilns, which ensure uniform drying through exact temperature adjustment. For instance, LPG-powered dryers preserved the nutritional value of grains and vegetables by maintaining fluctuations of ±2°C (Debowski *et al.,* 2021). These benefits are combined in hybrid systems, including solar-charcoal dryers, which cut fish fillet drying periods by 50% (90–160 minutes) while preserving hygienic requirements (Okusanya *et al.,* 2021). In areas with irregular gas supply, farmers favoured dual-fuel systems to lessen drying-out periods. Although they praised the hybrid units' long-term operational efficiency, local artists voiced concerns about their initial affordability. Transitioning from charcoal-only to hybrid kilns resulted in enhanced product consistency, according to several processors, suggesting a greater market preference for kiln-dried products of consistent quality.

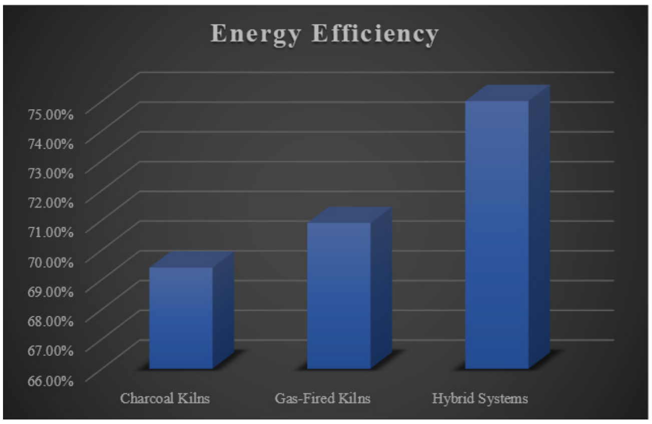

Figure 3: Graphical Representation of Energy Efficiency

Operational Flexibility and Fuel Interchangeability

Hybrid drying systems provide for crucial gas and charcoal interchangeability in areas with limited fuel supplies. Because charcoal is widely available locally, operators can quickly switch to it when gas becomes scarce (Nwakuba *et al.,* 2018). On the other hand, gas offers a cleaner substitute when charcoal supplies are scarce, allowing for continuous operation (Okusanya *et al.,* 2021). Dual combustion chambers and computerised controls for smooth transitions are features of contemporary hybrid kilns that guarantee continuous drying cycles. Farmers can utilise whatever fuel is available without sacrificing drying efficiency or product quality, which is especially useful in distant places where fuel shortages are frequent (Daramola *et al.,* 2020). Such devices offer a workable remedy for agricultural processing's energy volatility.

Economic and Operational Trade-offs

Although the initial costs of charcoal kilns are lower, long-term costs are increased by their labour-intensive maintenance and fuel inefficiency (Onyenanu *et al.,* 2023). Because of their cleaner combustion, gas kilns have lower operating costs but require 60–80% more capital investment (Akhtar *et al.,* 2015). Despite their initial expense, hybrid systems lessen reliance on fuel; for example, LPG-hard coal hybrids reduce energy consumption by 6.14% (Debowski *et al.,* 2021).

CONCLUSION

Charcoal kilns are inexpensive and widely available, especially in developing countries, but they have inefficiencies and higher emissions. On the other hand, gas kilns have better temperature control, energy efficiency (up to 70.9% exergy efficiency), and a lower environmental impact. Hybrid systems combine these advantages, reducing drying times by 50% while maintaining product quality. These findings indicate that hybrid solutions are ideal for striking a balance between efficiency and cost.

This study analyses gas drying and charcoal in agriculture in a novel way, highlighting the operational efficiency and fuel flexibility of hybrid systems. It provides engineers and farmers with a systematic performance framework that combines economic, mechanical, and thermal data to help them choose the best drying methods. By assessing dual-fuel adaptability, emissions, and rural scalability, this analysis fills the vacuum left by earlier studies that concentrated on single-fuel kilns. Evidence-based design, implementation, and policy planning for energy-resilient agricultural drying systems are supported by the findings.

LIMITATIONS

The study may have missed useful field data because it mostly concentrates on peer-reviewed literature. The findings' applicability may be limited by variations in local infrastructure and fuel availability. Environmental implications of charcoal production, such as deforestation, were not deeply quantified.

RECOMMENDATIONS

Future research should look into scalable hybrid systems based on regional fuel supply. Policymakers should encourage greener technologies, and farmers should use modular kilns for flexibility. Investments in renewable energy integration could improve overall sustainability.

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