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Drying Technologies for Nigerian Walnut (*Tetracarpidium conophorum*): A Review of Quality Characteristics and Processing Efficiency

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Abstract

Nigerian walnut (Tetracarpidium conophorum) is an underexploited nutritious nut which is rich in oil. The nut has great importance not only from nutritional and medicinal point of view but economically as well, especially in tropical countries. However, its high moisture content poses a problem of fast deterioration due to which it becomes very important to dry it before storing or processing. Therefore, this review article is focused on various technologies for drying Nigerian walnut and related oil rich nuts, with special reference to their impact on the quality of the nuts as well as ease of processing. Conventional drying techniques such as sun drying, solar drying, oven drying, and cabinet drying have been analysed along with new innovations in drying technologies. Studies show that increased drying temperature from 50 to 80°C decreases drying time from 7 to 8 hours to 4 hours and effective moisture diffusivity varies from 4.94×10^{-10} to 4.72×10^{-7} m²/s depending on drying methods used. Infrared drying can help decrease drying time from 240 min to 40 min while decreasing specific energy consumption from 31.56 MJ/kg to 7.76 MJ/kg. In addition, effects of different drying methods on quality attributes, the importance of proper drying process for increasing storage ability, minimizing post-harvest losses and making processing easy has also been mentioned. Nevertheless, energy usage, non-uniformity and quality degradation continue to be serious issues related to processing of Nigerian walnuts despite advances in drying technologies. There is a need for optimizing drying techniques as well as development of suitable drying processes for developing countries.

Keywords: Nigerian walnut; drying technologies; quality characteristics; processing efficiency; post-harvest processing; *Tetracarpidium conophorum*

Introduction

Nigerian walnut (*Tetracarpidium conophorum*) is an economically significant indigenous nut cultivated in several regions within West Africa owing to its nutritional and therapeutic significance (Obeta *et al*., 2022). The crop belongs to *Euphorbiaceae* family and it is primarily grown in southern Nigeria. The walnut plant produces fruits that are sources of income, nutrition, and medication for local communities (Oke *et al*., 2020). The nut seed contains high levels of proteins, fats, minerals, vitamins, and phytochemicals making the nut highly nutritious (Chauhan and Chauhan, 2020). Consumption of the nut helps in the improvement of cardiovascular function, antioxidant capacity and enhancement of reproductive function (Laddha *et al*., 2020). Nigerian walnut is cultivated mainly in the southern regions of Nigeria including states such as Ondo, Osun, Ogun, Enugu, and Rivers where climatic conditions favour its growth (Oke *et al*., 2020). Beyond Nigeria, the crop is also found in some parts of West and Central Africa. Although the crop remains underutilised compared to other commercial nuts, its production and consumption continue to increase due to growing awareness of its nutritional, medicinal and economic importance (Oke *et al*., 2020). Nigerian walnut contributes to household income generation, rural livelihood development and food security among local farming communities (Obeta *et al*., 2022).

However, poor postharvest handling and inadequate processing technologies continue to limit large-scale commercialisation and industrial utilisation of the crop. The freshly harvested walnut fruit has high moisture content that promotes the growth of microorganisms, biochemical degradation, and reduces the shelf life (Adkison *et al*., 2021). Drying is, therefore, essential in ensuring that moisture is reduced to safe levels in order to minimize wastages, prolong shelf life and improve marketability of the commodity. Drying processes utilized in the processing of walnuts include open sun drying, solar drying, hot air oven drying and cabinet drying (Yuan *et al*., 2025). These drying processes vary significantly in terms of drying effectiveness, energy requirements, drying time and impacts on the quality of the product (Bradford *et al*., 2020). If inappropriate conditions are utilized in the drying process, the dried walnut product is characterized by loss of quality and nutrients due to lipid oxidation, change in colour among others (Han *et al*., 2019). It is, thus, essential to choose the best drying method that ensures the quality of the dried nut.

Over the past few years, efforts have been intensified towards developing effective and sustainable methods of drying agricultural produce in order to promote industrial utilization of such crops. As such, there is need to understand the correlation between the drying process and quality characteristics of the product. This review paper aims at highlighting existing drying technologies for Nigerian walnut and other oil-rich nuts as well as their impacts on the quality characteristics of the dried product.

Overview of Nigerian Walnut

Botanical Description

The Nigerian walnut (*Tetracarpidium conophorum*) is a perennial climbing plant that belongs to the *Euphorbiaceae* family (Ayodeji and Aliyu, 2018). The plant can be commonly found in tropical rain forest areas of Nigeria and other parts of West Africa (Nkwonta *et al*., 2023). The plant bears nuts contained within a shell which can be eaten raw after being boiled or dried (Taskin et al., 2024a). The plant thrives in humid climate conditions and plays a great role in supplying people with nutrition (Onwuka *et al*., 2020).

Nutritional Value

Nigerian walnut is known for being an extremely nutritious foodstuff because of its high protein and lipid contents (Onwuka *et al*., 2020). Moreover, carbohydrate, fibre, mineral, and vitamin components were found in the nut (Obeta *et al*., 2022). In particular, researchers reported the presence of essential fatty acids, amino acids, and antioxidants in the plant, making it useful as both food and medicine (Adetunji *et al*., 2021; Jin *et al*., 2022; Matin *et al*., 2024). However, the nut is highly rich in oils, which makes it very sensitive to oxidation during storage (Gama *et al*., 2018).

Economic and Medicinal Significance

Apart from its food value, the Nigerian walnut demonstrates medicinal activity and is used in traditional health care (Obeta *et al*., 2022). Different parts of the plant were proven to have antibacterial, fertility improving, and antioxidant effects (Adetunji *et al*., 2021). From an economic perspective, walnut growing and trade can offer employment and income opportunities to people working on farms and in small factories (Oke *et al*., 2020). Therefore, the development of drying techniques for walnuts is economically important.

Drying Technologies Applied in Walnut Processing

Drying is one of the major post-harvesting operations used in the preservation of Nigerian walnut since it helps reduce moisture content and spoilage caused by microorganisms (Wu *et al*., 2024). Various drying technologies have been developed for drying processes in order to achieve specific drying objectives and quality of the final products (Nainggolan *et al*., 2024; There and Sharma, 2024). The choice of drying technology used in the process depends on several factors including energy source, process cost, drying rate and product quality.

Open Sun Drying

One of the oldest methods of drying applied traditionally to various agricultural products includes the use of open sun drying due to its simplicity and cost-effectiveness (Natumanya *et al*., 2021). The procedure entails the use of direct sunlight for removing moisture from walnut samples. The benefits of open sun drying include the use of low-cost or free technology, simple structure and low operating cost (Acar *et al*., 2022). The process is relatively slow, highly dependent on weather conditions, associated with possible contamination by dust and other particles, poor hygiene and uneven drying rate (Lal *et al*., 2026). In addition, prolonged exposure to solar radiation could lead to degradation of some quality attributes like flavour and appearance due to oxidation or enzymatic reactions (Akter *et al*., 2024). The method is extensively applied among local walnut processors mainly due to its affordability.

Solar Drying

Solar drying refers to the use of enclosed dryers that employ solar radiation as the main energy source for removing moisture (Shekata *et al*., 2024). It improves drying efficiency and hygienic quality of dried products (Fufa *et al*., 2025). Several types of solar dryers such as direct, indirect and mixed-mode solar dryers have been employed in drying different agricultural produce (El Hage *et al*., 2018). In direct solar dryers, the product is exposed directly to solar radiation inside an enclosure, whereas in indirect dryers, heated air is generated using a solar collector (Kabeel and Abdelgaied, 2018; Jayasuriya *et al*., 2023). Benefits of solar drying compared to the open sun drying technique include reduced drying time, higher hygienic quality and better retention of nutrients (Natumanya *et al*., 2021). Nevertheless, drying performance of solar dryers could be affected by fluctuations in solar radiation intensity and environmental weather conditions (Lingayat *et al*., 2020). Therefore, hybrid energy systems incorporating thermal energy storage have been explored to increase efficiency and reduce drying variability (Ibrahim *et al*., 2024).

Oven Drying

Oven drying represents a controlled process that is often used in laboratory and small-scale drying processes (There and Sharma, 2024). In this drying method, heated air circulation around the samples is achieved at certain set temperatures in order to remove moisture from the material (Li *et al*., 2026).

Benefits of oven drying include improved control over drying parameters such as temperature and air velocity; as a result, the method allows obtaining more uniform and rapid drying rate than traditional methods (Li *et al*., 2026). Therefore, the process is extensively applied in drying studies involving walnuts and other nuts (Dajbych *et al*., 2023; Wu *et al*., 2024; Ayoola *et al*., 2026).

Excessive temperatures, however, have negative effects on nutritional and sensory properties of the nuts due to protein denaturation, lipid oxidation and degradation of thermally sensitive bioactive compounds (Teneva *et al*., 2024). High energy requirement and costs of operation prevent the widespread application of the technology among processors in some developing countries (Zahid *et al*., 2025).

Cabinet Drying

Cabinet drying technique involves the use of enclosed cabinets designed with trays and forced circulation of heated air for the removal of moisture (Yasmin *et al*., 2022). The method has been widely used in food processing industries since it allows achieving higher efficiency of the process (Asrate and Ali, 2025). The use of cabinet dryers leads to more uniform distribution of heat energy that contributes to increased drying rate and reduced contamination by microorganisms (Asrate and Ali, 2025). Research findings reveal that the method effectively removes moisture from food materials with better retention of quality attributes at proper drying conditions (Arslan and Alibaş, 2024). The performance of the process depends on various parameters including drying temperature, air velocity, thickness and quantity of materials loaded into the dryer (Joo *et al*., 2024). Optimizing these variables is important for enhancing drying kinetics while reducing energy consumption.

Hybrid and Emerging Technologies

Development of advanced drying techniques in food processing industry has resulted in the creation of hybrid and energy-efficient technologies aimed at improving the drying process (Asrate and Ali, 2025). Examples of hybrid dryers involve combination of several processes such as solar-assisted dryers, heat pump dryers, microwave-assisted drying and infrared drying technology (Arslan and Alibaş, 2024).

These techniques show better drying kinetics, lower energy consumption and less quality degradation than traditional methods (Kaveh *et al*., 2025). For instance, microwave-assisted drying leads to faster diffusion of moisture due to rapid volumetric heating (Athira *et al*., 2023). Similarly, infrared drying shows efficient heat transfer with minimal damage to quality as the process takes less time compared to other methods (Gao *et al*., 2024).

Limited application of these advanced technologies is mainly attributed to high installation costs, complexity and lack of proper infrastructure in developing countries (Nwankwo *et al*., 2023; Viola Salvador *et al*., 2025). More researches and technological adaptations should be conducted in order to develop sustainable technologies for drying walnut. Table 1 shows a summary of different drying technologies used for walnut processing and their impacts on product quality.

Table 1. Quantitative effects of drying technologies on walnut quality and processing efficiency

Study	Drying Method	Major Quantitative Findings
Ayoola *et al*. (2026)	Cabinet and oven drying	Drying time decreased from 7–8 h at 50°C to 4 h at 80°C; effective moisture diffusivity ranged from 6.23×10^{-8} to 4.72×10^{-7} m²/s; SEC ranged from 0.11 to 2.93 kWh/kg
Man *et al*. (2024)	Hot-air drying	Effective moisture diffusivity ranged from 4.94×10^{-10} to 1.44×10^{-9} m²/s; activation energy ranged from 21.56 to 23.35 kJ/mol
Taskin *et al*. (2024b)	Infrared pre-drying + hot-air drying	Drying time reduced from 240 min (hot air) to 40 min (IR pre-dried kernels); SEC reduced from 31.56 to as low as 7.76 MJ/kg
Chen *et al*. (2020)	Hot-air drying	Pre-soaking increased drying time by approximately 2–4 h
Chen *et al*. (2020)	Step-down temperature drying	Drying time reduced by up to 40% and energy consumption reduced by 24% without compromising walnut quality
Yuan *et al*. (2025)	Vacuum freeze, microwave, hot air, vacuum and natural drying	Vacuum freeze drying produced the highest protein content (21.41 mg/g), phenolic content (212.08 mg/g), antioxidant activity (84.11%), and rehydration capacity (90.61%)

Wu *et al*. (2024)	Oven drying vs natural air drying	Oven drying produced lighter kernels and superior quality retention compared with natural air drying

Effect of Drying on Quality Characteristics

The effectiveness of the drying procedure has a direct impact on the quality of Nigerian walnut and similar fruits. In addition to their effect on nutritional content, drying parameters determine the physical and sensory quality of the resulting products (Osae *et al*., 2023). Optimal drying is an important consideration that affects the safety, stability, and consumer acceptance of dried products. Quantitative studies have established that the process of drying has a great impact on the qualities of walnuts. According to Yuan *et al*. (2025), vacuum freeze-dried walnuts had the highest protein content (21.41 ± 0.73 mg/g), phenolic content (212.08 ± 2.06 mg/g), antioxidant capacity (84.11 ± 0.88%), and hydration ratio (90.61%) amongst the five techniques of drying. The microwave drying and vacuum freeze-drying had sensorial properties closest to that of fresh walnuts, whereas hot air drying had more favourable impacts on roasted flavour compounds formation as well as higher levels of amino acids and fatty acids. Likewise, Wu *et al*. (2024b) found that the dried walnuts in oven drying were plump and yellowish-white while those in natural air drying were darker and wrinkled.

Moisture Content and Shelf Stability

As is well known, one of the key purposes of the drying process includes reducing moisture content to ensure the safety and stability of the products in storage (Menon *et al*., 2020). The natural moisture content of fresh Nigerian walnut is relatively high and may cause quick deterioration during storage (Onwuka *et al*., 2020). Drying effectively reduces moisture content and activity, thus increasing shelf stability and extending storage life (Abbaspour-Gilandeh *et al*., 2020). Lowering moisture content helps inhibit the development of harmful microorganisms such as moulds and bacteria causing deterioration of agricultural products in storage (Mafe *et al*., 2024).

Research has shown that the rate of moisture removal and resulting final moisture content depend largely on drying temperature and duration (Ayoola et al., 2026). As a general rule, higher temperatures enhance the moisture diffusion process, but excessive heating may reduce the quality of the products (White *et al*., 2025). Thus, proper conditions should be ensured in order to maximize the efficiency and effectiveness of drying.

Effect on Proximate Composition

Nutrient composition of food products may change due to the drying procedure depending on the particular methods used and drying parameters chosen (Khaled *et al*., 2024). Changes in nutrient composition are usually associated with thermal degradation, oxidation reactions and concentration effects that occur during moisture removal (ElGamal *et al*., 2023).

It has been shown that protein content remains relatively stable even after drying at moderate temperatures, although excessive heating may cause denaturation and degradation of proteins (Manju *et al*., 2021). Similarly, the fat content may be affected adversely due to lipid oxidation caused by prolonged drying at elevated temperatures (Piskov *et al*., 2020).

On the other hand, the moisture removal process leads to an apparent increase in other components, such as fiber and ash, in dried products (Abbaspour-Gilandeh *et al*., 2021). The exact nature of these effects depends on the drying method chosen and the parameters of drying. In any case, proper control of the drying process is important for the effective preservation of nutrients in Nigerian walnuts.

Effect on Phytochemicals and Antioxidant Properties

Bioactive phytochemicals contained in Nigerian walnuts make them valuable for medicinal uses and health benefits (Nguyen and Vu, 2023). However, phytochemicals are rather sensitive to drying operations and their content may be changed significantly during processing (Paramanandam *et al*., 2021).

High temperatures and prolonged heat treatment may impair significantly the antioxidant capacity of the products by affecting their phenolic content (Narra *et al*., 2024). Properly controlled drying at moderate temperatures helps retain phytochemicals and increase the stability and storability of the products (Paramanandam *et al*., 2021). It has been found that controlled methods of drying such as cabinet and solar drying result in higher content of bioactive compounds in comparison with traditional open sun drying (Akther *et al*., 2023). Preserving phytochemicals in processed products contributes positively to their nutritional value and functionality.

Effect on Colour, Texture and Sensory Properties

Colour and texture are important quality characteristics that directly affect the consumer acceptability of dried food products (Özdoğan *et al*., 2021). Drying conditions are important factors influencing these characteristics of dried Nigerian walnuts (Nyawo *et al*., 2025).

High temperatures may cause the Maillard reaction, a non-enzymatic browning process, leading to darker color of dried walnuts (Pedron *et al*., 2025). On the other hand, prolonged drying leads to hardening of the products and decrease in their palatability (Alemayehu *et al*., 2026).

In addition, drying methods providing more stable temperatures, such as cabinet or oven drying, are able to produce a more uniform and homogeneous product with good sensory characteristics (Lal *et al*., 2026). Solar drying may improve the hygienic quality of the products, reducing their contamination while preserving their colour and flavour (Lal *et al*., 2026).

Good sensory qualities are required for achieving consumer acceptability of dried walnuts.

Lipid Oxidation and Oil Stability

Since Nigerian walnuts contain a lot of oil, they are susceptible to oxidation which is a major factor in quality deterioration of food products (Ampofo *et al*., 2022). Lipid oxidation is a chemical reaction that leads to formation of peroxides and other harmful substances, decreasing the nutritional value of the products (Liu *et al*., 2023).

Drying temperature is one of the main factors affecting the rate of oxidative reactions in dried products (Kic, 2019). Drying at high temperatures increases the risk of lipid oxidation and formation of harmful compounds (Xu *et al*., 2024).

Thus, optimal drying conditions play an important part in minimizing lipid oxidation in dried walnuts. Table 2 summarizes the various effects of drying on quality characteristics of Nigerian walnut.

Table 2. Effects of drying on quality characteristics of Nigerian walnut

Quality Parameter	Effect of Drying	Major Influencing Factors
Moisture content	Significant reduction in moisture content leading to improved shelf stability and reduced microbial spoilage	Drying temperature; drying time; air velocity; drying method
Protein content	Generally stable under moderate drying conditions, but excessive heating may cause protein denaturation	Temperature; drying duration
Fat stability	High temperatures may accelerate lipid oxidation and rancidity development	Drying temperature; oxygen exposure; drying duration
Ash content	Apparent increase may occur due to moisture reduction and concentration effects	Moisture loss; drying intensity

Fibre content	Slight increase may be observed as a result of concentration during drying	Moisture reduction; drying conditions
Antioxidant properties	Prolonged or excessive heating may reduce antioxidant activity and phytochemical content	Temperature; exposure time; drying method
Colour	High temperatures and prolonged drying may cause browning and colour deterioration	Temperature; drying duration; heat exposure
Texture	Excessive drying may lead to hardening and reduced palatability	Moisture removal rate; drying temperature
Sensory quality	Drying conditions influence flavour, appearance and overall acceptability	Drying method; temperature; processing conditions
Shelf life	Proper drying enhances storage stability and reduces postharvest losses	Final moisture content; storage conditions

Source: Compiled from literature review (Chauhan and Chauhan, 2020; Laddha *et al*., 2020; Oke *et al*., 2020; Piskov *et al*., 2020; Adetunji *et al*., 2021; Obeta *et al*., 2022; Qingyang *et al*., 2023; Matin *et al*., 2024).

Processing Efficiency and Energy Considerations

Processing efficiency is an important aspect in choosing and evaluating appropriate drying technologies for agricultural products such as Nigerian walnut. An efficient drying technology must be able to remove moisture quickly while using as little energy as possible and ensuring product quality (Chojnacka *et al*., 2021). This is particularly important in developing nations where energy prices and availability are major concerns. There are significant differences in efficiency between the various forms of drying technology applied in drying walnuts. According to Ayoola *et al*. (2026), an increase in drying temperature from 50°C to 80°C led to a decrease in drying time from around 7-8 hours to 4 hours under both cabinet and oven drying methods. The effective moisture diffusivity increased from 6.23×10^{-8} to 4.72×10^{-7} m^2/s, suggesting that higher temperatures improve moisture migration while the activation energy ranged from 4.79 to 24.61 kJ/mol depending on the type of drying system used and the shell status. The specific energy consumption range was also wide, ranging from 0.11 to 2.93 kWh/kg of water lost, but the best combination of drying rate and energy efficiency was provided by oven drying at 80°C.

Similar results were observed by Man *et al*. (2024). The researchers noted that effective moisture diffusivity of hot-air drying ranged from 4.94×10^{-10} to 1.44×10^{-9} m^2/s, while activation energy ranged from 21.56 to 23.35 kJ/mol. Increased drying temperature increased moisture diffusivity and mass transfer coefficient, therefore reducing drying time and improving drying efficiency. There is evidence to suggest that advanced drying technologies are more efficient than hot air-drying methods. For example, Taskin *et al*. (2024b) noted that intact-shell walnuts needed about 240 minutes when using conventional hot-air drying. However, infrared pre-dried kernel only took 40 minutes. Additionally, the specific energy consumption in conventional hot-air drying was much higher compared to infrared-assisted drying, at 31.56 MJ/kg and as low as 7.76 MJ/kg respectively. Similar results were reported by Chen *et al*. (2020), where step-down temperature drying reduced drying time by up to 40% and energy consumption by 24%.

Drying Rate and Moisture Removal Efficiency

Drying rate refers to the quantity of water removed by the product during drying per unit of time; it is affected by the temperature used, air velocity, product thickness and drying mode (Khodadadi and Masoumi, 2025). Higher temperatures generally increase the heat transfer rate and accelerate diffusion of moisture from product surfaces, hence decreasing drying time (Mansour *et al*., 2025).

Cabinet and oven drying techniques have higher moisture removal rates than open sun drying owing to the better regulation of temperature and airflow (Ayoola et al., 2026). The goal should be a fast and uniform moisture removal so as to decrease drying time while avoiding bacterial contamination during processing (Asrate and Ali, 2025). Excessive drying rates, however, can cause undesirable quality alterations such as case hardening, product shrinkage and nutrient destruction (Yang *et al*., 2024). Thus, it is necessary to appropriately optimize drying conditions in order to remove moisture efficiently without compromising quality.

Energy Consumption during Drying

Utilization of energy is another key economic consideration in drying operations as large amounts of heat are used during the drying process (Urbano *et al*., 2023). Traditional drying systems like hot-air ovens and cabinets usually consume lots of electricity or thermal energy, which adds to processing cost (Bhattacharjee *et al*., 2024). The efficiency of energy utilization is dependent on factors like drying temperature, time, insulation efficiency and airflow management within the dryer (Maysami *et al*., 2020). Poorly engineered drying systems can suffer from unnecessary heat losses, leading to poor processing efficiency (Yu *et al*., 2025). Therefore, efforts have been made towards optimizing the energy efficiency of drying processes by designing solar-based and hybrid drying systems (Parhizi *et al*., 2022). The use of solar energy makes drying more efficient by reducing dependency on traditional fuel sources, hence reducing operating costs (There and Sharma, 2024). Hybrid systems have proved to offer increased energy efficiency and reduced drying time compared to single drying modes (Mierzwa and Musielak, 2023).

Economic and Sustainability Aspects

The economic feasibility of drying technologies is critical especially in cases involving small-scale processors in developing countries (Machala *et al*., 2022). Traditional open-sun drying has remained a common practice due to relatively low initial costs although it faces certain disadvantages like low drying efficiency and quality problems (There and Sharma, 2024). Modern drying technologies such as cabinet drying, heat pump drying and microwave-assisted drying provide greater drying efficiency but require high capital investments and technical knowledge (Yu *et al*., 2026). Thus, there has been a need for cost-effective and energy-efficient drying systems that fit rural and small-scale operations. Environmental and sustainability issues have become increasingly important in agricultural processing industries since they affect energy efficiency and ecological balance. The application of renewable sources of energy such as solar energy contributes immensely to sustainable agricultural processing and reduction of carbon footprint (Majeed *et al*., 2023). Optimization of the drying process can thus enhance the efficiency and sustainability of drying technologies used in walnut processing industry (Ayoola et al., 2026).

Optimization of Drying Conditions

It is critical to optimize the various parameters for attaining desired product quality and processing efficiency. These parameters include drying temperature, air velocity, drying time and product thickness (Asrate and Ali, 2025). They greatly affect moisture removal process, energy consumption and quality preservation (Ntsowe *et al*., 2025). Statistical and mathematical optimization methods have been applied to determine appropriate drying conditions for agricultural products (Elwakeel *et al*., 2025). It would help to reduce drying time, improve energy efficiency and prevent quality damage during processing (Taghinezhad *et al*., 2021). Nigerian walnut would require further optimization studies to determine optimal drying conditions that would balance efficiency and quality aspects of drying. Figure 1 shows the flowchart illustrating Nigerian walnut drying technologies, drying conditions, quality outcomes, and processing efficiency. The diagram highlights the influence of different drying methods and operating conditions on moisture reduction, shelf stability, nutrient retention, oil stability, sensory quality, and overall market value of dried Nigerian walnut.

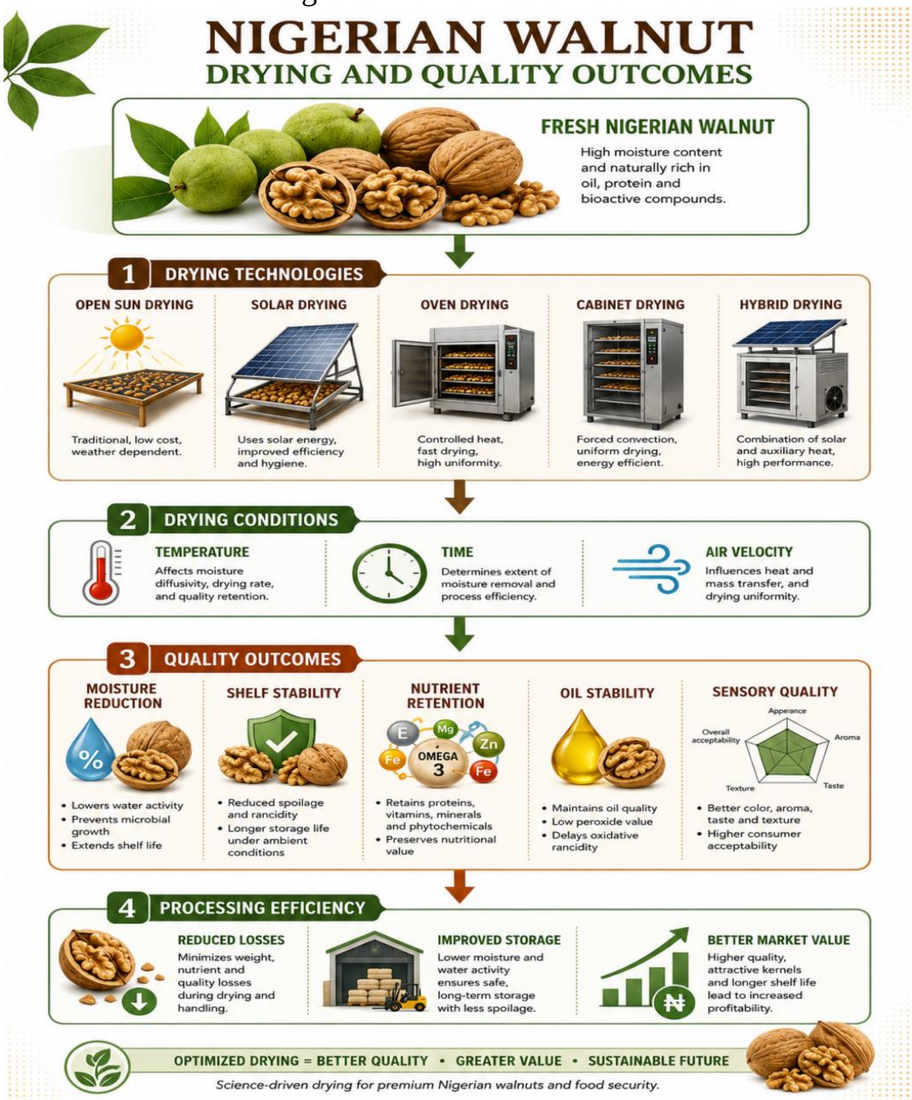

Figure 1. Flowchart of Nigerian walnut drying technologies, drying conditions, quality outcomes, and processing efficiency.
Source: Author's conceptual illustration based on literature review.

Challenges and Future Research Directions

In spite of the increasing importance being attached to post-harvest technology and the utilization of Nigerian walnuts, many challenges exist which hinder effective and efficient drying process. These challenges include some factors which affect quality, efficacy, processing efficiency, and commercialization of walnut products. One of the most important challenges facing walnut producers in the drying process is the high energy demand required by conventional dryer types (Urbano *et al*., 2023). Rising energy costs, as well as lack of stable electricity supply in developing countries, make the operation of new technologies too costly and thus inaccessible to many processors (Ugembe *et al*., 2023). Therefore, some processors have no option but to use traditional open-sun drying methods which are unhygienic, prone to environmental contamination, and do not yield good results. Other challenges include the inability to create optimum drying conditions that preserve the quality of dried products. High drying temperatures and long drying periods can lead to loss of nutrient content, lipid oxidation, reduced colour value, as well as poor sensory properties of walnut products (Yang *et al*., 2024). Inefficiency during drying processes could therefore adversely impact the nutrition and commercial value of the final product. Other problems associated with drying of Nigerian walnut include limited availability of suitable drying equipment as well as lack of adequate technical skills among processors (Ayoola et al., 2026). Traditional methods are often used where there is inadequate monitoring of critical drying variables such as temperature, airflow, and moisture content (Qingyang *et al*., 2023). As a result, uniformity and quality of dried walnuts are adversely affected.

Future research needs to focus on development of cost-effective, energy-efficient and eco-friendly drying techniques for drying products in resource-limited regions. Special emphasis should be placed on hybrid drying techniques which offer a wide range of benefits. There is also a need for more research into the optimization of drying parameters in order to improve quality and efficiency of the drying process. Mathematical modelling techniques could be employed to gain better understanding of the drying process. Further research should also be conducted on the impact of drying on bioavailability of natural antioxidants in dried walnuts as well as their storage properties. In addition, there is need for closer cooperation among agricultural engineers, food processors, and other stakeholders to ensure wider industrial utilization of Nigerian walnuts. Improvement in postharvest technologies and creation of value-added walnut products could go a long way in improving food security and rural livelihoods.

Conclusion

Dryer technology is important in improving shelf life, safety and processing quality of Nigerian walnut (*Tetracarpidium conophorum*). Diverse types of dryer technology ranging from open sun drying, solar drying, oven drying and cabinet drying affect product quality and processing efficiency to different extents. Optimized conditions for drying are required for the conservation of the nutrient composition, phytochemical components, sensory attributes and oil stability in order to prevent any further degradation during storage. While conventional drying technology continues to be practiced owing to its economic benefits, new dryer technologies that are both cost-effective and efficient have emerged. More research efforts towards optimizing drying process parameters and developing sustainable dryer technologies are warranted.

This review compiles current research findings on drying technologies of walnuts, which include reports on drying time from 40 minutes to 8 hours, moisture diffusivity rate from 4.94×10^{-10} to 4.72×10^{-7} m^2/s, activation energy from 4.79 to 24.61 kJ/mol, and savings in energy utilization up to 24% via improved drying technologies. This review additionally explores the impacts of the use of drying technologies on the nutritional value, retention of antioxidants, flavour formation, and efficiency in processing.

Declaration of Competing Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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