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# Roadside Open Sun Drying in Nigeria: Food Safety Risks and Potentials of Solar Drying technologies as mitigating strategies

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A B S T R A C T

Roadside open sun drying remains the dominant post-harvest food preservation method among smallholder farmers and rural agro-processors across Nigeria, driven by zero operational cost, cultural tradition and the absence of possible alternatives. Despite its economic rational, the practice systematically exposes commodities to dangerous arrays of chemical, microbial and physical contamination hazards. Chemical risks often arise from vehicular emissions depositing heavy metals, polycyclic aromatic hydrocarbons and volatile organic compounds on the drying produce, while direct contact with bituminous road surfaces introduces hydrocarbon residues. Microbial hazards include contamination by pathogenic bacteria, mycotoxigenic fungi, and zoonotic vectors, compounded by slow and interrupted drying cycles that aid conditions favorable to aflatoxin-producing fungi and enteric pathogens. Physical contaminants including dust, insect fragments and animal droppings further compromise product safety, quality and marketability. These cumulative hazards impose a great public health concern on Nigerian consumers, particularly vulnerable populations including children and women. Improved solar drying technologies like cabinet, tent, direct, indirect, and hybrid solar-biomass systems represent evidence-based mitigation strategies that address these hazards while preserving the solar-powered, low-operational-cost nature of traditional drying. These enclosed systems achieve increased drying temperatures, rapid moisture removal, and exclusion of environmental contaminants and thermal inactivation of pathogens, producing commodities that consistently meet NAFDAC, SON, and international food safety standards, thereby unlocking premium domestic and export market access currently unavailable to open sun-dried products. Despite these demonstrated food safety and economic benefits, adoption of improved solar dryers among Nigerian smallholders remains critically low, constrained by high initial capital costs, limited technical awareness, inadequate extension services and weak regulatory enforcement. This review consolidates current evidence on the food safety risks of roadside open sun drying, evaluates the mitigating role of improved solar drying technologies and opportunities necessary to safeguard public health across Nigeria's food value chain.



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## 1. Introduction

Drying is one of the oldest and most fundamental food preservation method, leveraging the reduction for water activity to inhibit microbial growth and enzymatic degradation (Talib et al., 2024). In Nigeria, as across much of sub-Saharan Africa, sun or open air drying remains the dominant drying technique, practiced by an estimated 70–80% of smallholder farmers and rural food processors (FAO, 2019; Amoah, 2024). This drying method requires no capital investment beyond the commodities themselves and the ambient solar radiation that Nigeria receives in abundance, averaging between 3.5 and 7.0 kWh/m² per day across different agro-ecological zones (Ojeleye, 2025). Small-scale processors and farmers are seen on the major highways or in domestic settings spreading freshly harvested or semi-processed foods directly on roadsides, pavements and rooftops to harness ambient solar radiation for moisture removal. The persistence practice of this roadside open sun drying is driven primarily by its low capital requirements, ease of implementation, and deep roots in traditional preservation knowledge, making it an economically rational choice for resource-constrained individuals in Nigeria's food sector (Olanipekun et al., 2025; Olagunju, 2021).

Despite its popular adoption and economic advantages across the country, food products are exposed to a complex array of environmental contaminants during drying and these may pose significant public health risks (David et al., 2019; Bolade, 2016; Alp & Bulantekin, 2021; Oyero et al., 2024).

The public health consequences of these hazards are poorly quantified but potentially severe. Nigeria records one of the world's heaviest burdens of food-borne illness, with the World Health Organization estimating that Africa had approximately 91 million food-borne illness cases and 137,000 deaths reported annually (WHO, 2015; Kumar et al., 2024).

However, awareness among practitioners about the cumulative health risks associated with atmospheric deposition on sun-dried products remains limited, contributing to the continued reliance on this potentially hazardous method (Ogunlade et al., 2021). These food safety risks associated with roadside open sun drying can be categorized into three principal causes: microbial, chemical, and physical contamination.

Mycotoxin contamination, a direct consequence of poor drying conditions is one of the major endemic in Nigerian food supply chains, with aflatoxin levels in groundnuts, maize, and sorghum frequently exceeding both Nigerian regulatory limits and the more stringent standards of the European Union (Afolabi et al., 2015; EFSA, 2020). Heavy metal contamination from lead and cadmium deposited by roadside vehicular emissions has been documented in commodities dried along highways (Boahen, 2024; David et al., 2019).

The inherent limitations of traditional open sun drying give rise for the urgent need for alternative postharvest processing technologies that can maintain the economic accessibility of sun energy, as well as substantially reducing contamination risks. Diverse field studies have consistently demonstrated that open sun-dried samples exhibit higher heavy metal deposits and greater microbial loads than products dried using improved solar drying systems (Ogunlade et al., 2021; Taiwo et al., 2026). Improved solar drying technologies represent a promising pathway to address the food safety challenges of roadside open sun drying while preserving the low-cost, solar-powered nature of traditional methods. These technologies including solar cabinets, tents, parabolic dryers, and tray systems which employ enclosed or semi-enclosed designs that gives increased drying temperatures, increased moisture removal and reduce direct exposure to airborne contaminants.

Some researchers have conducted several field trials on the Parabolic Shaped Solar Dryer (PSSD) constructed by Nigerian Stored Products Research Institute reporting higher mean drying temperatures and faster drying rates than open sun methods, with corresponding reductions in bacterial counts, although fungal presence under certain conditions indicates that design and hygiene protocols critically influence outcomes (Ade et al., 2018; Joel et al., 2024; Ajao et al., 2025).

Solar tent and cabinet dryers have demonstrated reductions in heavy metal contamination and improved hygienic handling in controlled comparisons, with solar tent drying producing lower levels of lead, cadmium, and other contaminants compared with roadside open sun drying (Adenitan et al., 2022).

The mechanisms responsible for these risk reductions include higher controlled temperatures that inhibit microbial growth, enclosed airflow that limits deposition of vehicular emissions and particulate matter, and physical barriers that prevent direct contact with street dust and debris (Ade et al., 2018; Ajao et al., 2025; Kiritkumar, 2026). This review therefore examines the state of roadside open sun drying in Nigeria, food safety risks associated with it and to evaluate how improved solar drying technologies can mitigate these hazards in the Nigerian context.

## 2. Literature review

Nigeria, situated within the tropical sun belt (latitudes 4°–14° N), receives an average daily solar irradiance of 5.25 kWh/m$^2$ and approximately 6.5 hours of sunshine year-round, presenting immense potential for solar drying applications (Julius & Balogun, 2022; Oji et al., 2012).

With this substantial solar energy potential, solar dryers are increasingly promoted as an alternative to roadside open sun drying, especially for smallholder farmers and agro processors.

A national review shows that, despite many experimental designs and prototypes, traditional open-air sun drying still dominates because it is cheap, requires no technical skills, and has no size limitation (Zuluaga-Domínguez & Nieto-Veloza, 2025). However, studies have demonstrated that solar dryers can achieve higher drying temperatures, lower relative humidity, shorter drying times, and better product quality than open sun drying (Ade et al., 2018; Joel et al., 2024; Oyewole et al., 2023; Ajao et al., 2026).

Recognizing this endowment, the Nigerian Stored Products Research Institute (NSPRI), in collaboration with Federal government of Nigeria and international partners, has pioneered the development and field testing of several improved solar drying technologies tailored to Nigerian agro-ecological zones and commodity profiles (Joel et al., 2024; Adenitan et al., 2021).

The Institute has developed some arrays of diverse solar dryers ranging from mobile solar tent dryers, greenhouse solar tent dryers and parabolic solar tent dryers, achieving chamber temperatures up to 78 °C with lower relative humidity than ambient, and successfully drying beef, fish, chilli pepper, yam, vegetables and plantain to safe moisture levels within a few days (Ade et al., 2018).

Other Nigerian designs, such as improved smart solar dryers and low-cost tunnel dryers, have reduced drying time for maize, plantain, tomatoes and mangoes by 30–50% relative to open sun drying under local conditions, while remaining economically viable for rural users (Princewill et al., 2023; R et al., 2024).

Also, some experimental research on solar drying in Nigeria have been carried out by various scholars in the country (Lawrence et al., 2013; Okoroigwe et al., 2013; 2015; Aremu et al., 2020; Itoje et al., 2020; Aderemi et al., 2021; Okonkwo & Ertekin, 2022; Olaoye et al., 2023; Okoronkwo et al., 2024; Oyefeso et al., 2025; Akinsade et al., 2025).

A lot of significant works on solar drying have been carried out by them even though its potential is greatly under-utilized due to various factors militating against it. Despite these promising results, adoption remains limited by initial cost, need for basic technical know-how, and lack of farmer awareness, so the large food safety and quality potential of solar drying in Nigeria is still underutilized (Okonkwo & Ertekin, 2022; Ade et al., 2018).

## 3. Methodology

### 3.1 Review Design and Scope

This study adopted a narrative review methodology to systematically consolidate existing evidence on the food safety risks associated with roadside open sun drying in Nigeria and to evaluate the mitigating potential of improved solar drying technologies. The review was guided by three overarching research questions: (i) What are the predominant food safety hazards (chemical, microbial, and physical) associated with roadside open sun drying in Nigeria? (ii) How effectively do improved solar drying technologies mitigate these identified hazards? (iii) What socio-economic, policy, and technical factors constrain the adoption of improved solar drying systems among Nigerian smallholders and agro-processors?

### 3.2 Literature Search Strategy

A comprehensive literature search was conducted across multiple electronic academic databases including Google Scholar, PubMed, Scopus, Web of Science, ScienceDirect, and the Food and Agriculture Organization (FAO) digital library.

Additional grey literature was retrieved from the institutional repository of the Nigerian Stored Products Research Institute (NSPRI), the National Agency for Food and Drug Administration and Control (NAFDAC), the Standards Organisation of Nigeria (SON), the World Health Organization (WHO), and the European Food Safety Authority (EFSA).

The search covered publications from 2003 to 2026, with an emphasis on peer-reviewed primary research and review articles published from 2015 onward to ensure currency of evidence.

The search was conducted using Boolean operators (AND, OR, NOT) applied to the following keyword clusters: (i) “open sun drying” OR “roadside drying” OR “traditional sun drying” AND “Nigeria” OR “West Africa” OR “sub-Saharan Africa”; (ii) “food safety” OR “food contamination” AND “drying” AND “Nigeria”; (iii) “heavy metals” OR “polycyclic aromatic hydrocarbons” OR “aflatoxin” OR “mycotoxin” AND “sun-dried food” OR “dried agricultural produce”; (iv) “solar dryer” OR “solar drying technology” OR “cabinet dryer” OR “tent dryer” OR “hybrid solar dryer” AND “food safety” OR “Nigeria”; and (v) “postharvest loss” OR “smallholder farmers” AND “drying technology” AND “Nigeria”.

Reference lists of all retrieved articles were also manually screened to identify additional relevant studies not captured by the primary database search.

## 4. Roadside Open Sun Drying: Practices and Prevalence

Roadside open sun drying is one of the oldest methods of drying used predominantly by small holder farmers and agro processors across the six geopolitical zones in Nigeria. Nigeria is Africa's most populous country and one of its largest agricultural economies, with agriculture contributing approximately 24% of Gross Domestic Product (GDP) and employing over 70% of the rural labor force (NBS, 2022; Nwankwo et al., 2024).

The country produces a diverse range of food commodities including grains (maize, sorghum, millet, rice, etc.), legumes (groundnuts, cowpeas, and soybeans), roots and tubers (cassava, yam, sweet potato, etc), fish and meat products, fruits, and vegetables (Petrikova et al., 2023).

Virtually all these commodities require some form of post-harvest drying to achieve safe moisture levels for storage and trade (Shehu et al., 2018). This practice is commonly used for the drying of stable foods across the country by using the direct sun radiation and wind on unraised surfaces or platform along the highways, rural roads, pedestals, etc (Figure a-f). The practice slightly varies by commodity, regions and socio-economic status of the processor.

### 4.1 Operational mechanism of roadside open sun drying

This method of drying is defined by three distinct spreading surfaces, with each having different contamination pathways:

#### 4.1.1 Bituminous/concrete Road Surfaces

This involves spreading agricultural commodity directly on asphalt or tarred and concrete roadsides. It is commonly practice in urban-periurban interfaces, this method leverages the high thermal conductivity of the blacktop to accelerate moisture evaporation. This approach is ensure for a direct contact between food and hydrocarbon-laden surfaces, with temperatures often exceeding 60oC, causing asphalts residues getting into the food or dried products (Jayaneththi et al., 2024).

#### 4.1.2 Bare earth and compacted soil

This is predominantly explored in rural settlements where tarred roads are not available, produce are spread on bare ground. Even with the absence of hydrocarbon contamination, this method also exposes food to soil-borne pathogens, nematodes and dust (Bolade, 2016; Olowoyo et al., 2026). Produce are spread on ground level without been raised, thereby causing increase vulnerability to splash contamination during unexpected rainfall and infestation by crawling insects, droppings of birds and animal settling on the produce (Adenitan et al., 2022).

#### 4.1.3. Improved barriers (Polythene sheets and mats)

A slightly improved method involving the use of low-density polythene (LDPE) sheets, woven raffia mats or discarded tarpaulins (Amoah, 2024). These provide a physical separation from the ground, although they are often non-food grade, prone to tearing and difficult to clean (Mahamat et al., 2026). Degraded plastics can fragment into the produce, and water pooling on uneven sheets creates microenvironments for microbial proliferation. These materials doesn't stop infestation by insects or birds perching on the products while drying.

### 4.2 Commodity specificity and geographical distribution

**4.2.1 Roots and Tubers**: Cassava (Manihot esculenta) chips and yam slices are extensively dried on roadsides in Southwest (Ogun, Oyo, Osun) and South-South states (Ayantoye, 2021). The high carbohydrate content makes them particularly susceptible to rapid fungal colonization if drying is delayed (Bolade, 2016; Taiwo et al., 2026)

**4.2.2 Cereals and Legumes:** Maize, sorghum, millet, and cowpea are commonly dried on roadsides in the Northern geopolitical zones (Kano, Kaduna, Katsina, Jigawa, etc). These grains are often spread directly on tarred surfaces near major markets and collection centers (Ayeni et al., 2021).

**4.2.3 Spices and Vegetables:** Chili peppers, tomatoes, okra, leafy vegetables (e.g., Telfairia occidentalis, Amaranthus spp., etc.), and herbs are dried in thin layers across all regions (Okaiyeto et al., 2020). Their high surface-area-to-volume ratio accelerates both drying and contaminant adsorption (Oyedele et al., 2021).

**4.2.4 Fruits and Seeds**: Mango slices, pineapple rings, melon seeds (egusi), and sesame are increasingly dried using open sun drying for export and domestic markets, though quality inconsistencies often limit their market value (Okaiyeto et al., 2020).

### 4.3 Socio-Economic and Cultural Drivers of Persistence in Roadside Open Sun Drying

The persistence practice of roadside open sun drying is not just a function of tradition but a rational economic response to structural constraints faced by many Nigerian smallholders, rural farmers and traders.

**4.3.1 Zero Operational Cost:** Roadside open sun drying requires no fuel, electricity, or capital investment in equipment. For resource-poor farmers operating on razor-thin margins, the "free" nature of solar energy is the primary determinant of technology choice (Olagunju, 2021; Balana et al., 2024).

**4.3.2 Energy Poverty:** With rural electrification rates remaining low and the cost of diesel/petroleum prohibitive, mechanical drying is economically unviable for most small-scale processors. The intermittent nature of the national grid further precludes the use of electric dryers.

**4.3.3 Scalability and Simplicity:** Roadside open sun drying can be scaled up or down instantly by simply increasing the spreading area (Nainggolan et al., 2024). It requires no technical expertise to operate, making it accessible to all demographic groups, including women and youth who dominate postharvest processing (Adejuwon et al., 2023).

**4.3.4 Market Proximity:** Drying on roadsides often occurs at or near collection points and markets, reducing transportation costs for bulky, high-moisture fresh produce. Processors can dry and sell within the same location, minimizing logistics (Bello et al., 2022; Tyohemba et al., 2025).

#### 4.3.5 Cultural and Behavioral Dimensions

The persistence practice of roadside sun drying goes beyond only economics, it is as well fuelled by cultural believes and risk perception. Many processors or practitioners perceive the "sun-baked" flavor and texture of roadside-dried products as desirable, associating them with traditional authenticity (Kimaro et al., 2024). Also, there is a limited awareness of the invisible hazards (e.g., heavy metals, aflatoxins, etc) associated with the practice; contamination is often only recognized when visible dirt or mold is present.

This optimism bias, coupled with the immediate economic pressure to preserve harvests, sustains the practice despite growing public health warnings. In actual sense, drying by the roadside is a deeply embedded socio-technical system driven by economic necessity, infrastructural deficits, and cultural norms. While it provides a critical stop gap against postharvest losses, its operational modalities inherently compromise food safety (Israel et al., 2026).

Understanding these drivers is prerequisite to designing interventions such as improved solar dryers that are not only technically advanced but also economically accessible and culturally acceptable to the target end user (Balana et al., 2024).

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Figure a-f: Images showing roadside drying practices in some locations in Nigeria

## 5. Food safety risks of roadside open sun drying

Food safety continues to be a major concern as the supply chain of food products is so diverse and complicated (Flynn et al., 2019). Food safety can be compromised by several factors including but not limited to adulteration, bacterial contamination, mycotoxins, and allergen cross-contact. The food safety risks associated with roadside open sun drying can be categorized into three broad causes: microbial, chemical and physical contamination. The practice exposes food or produce to series of contamination hazards that compromise food safety and public health in Nigeria (Osei-Kwarteng et al., 2024).

### 5.1 Chemical Contamination: Heavy Metals and Hydrocarbons

Heavy metals and combustion related pollutants are often released from moving vehicles and other anthropogenic sources along the roadside where food products are spread (Boahen, 2024). The accumulation of these chemical and harmful waste is as a result of the proximity of drying sites to vehicular traffic caused by exhaust emission, tyre wear particles and suspended road dust. This results in the deposition of hazardous chemical species that are not removed by subsequent washing or milling (Roy et al., 2022).

#### 5.1.1 Heavy Metal Accumulation

Food commodities dried along roadside or highways where vehicles moves are often exposed to emissions containing lead (Pb), cadmium (Cd), nickel (Ni), zinc (Zn), copper (Cu), and particulate-bound polycyclic aromatic hydrocarbons (PAHs) (Boahen, 2024; Kumar et al., 2025). These metals originate from fossil fuel combustion, lubricating oils, and asphalt degradation. Studies on plantain chips and other roadside foods show significantly higher levels of Cd, Co and Pb in open sun–dried or marketed samples than in products dried in protected solar systems (Adenitan et al., 2022; Taiwo et al., 2026; David et al., 2019). The accumulation of these contaminants differs in respect to traffic density and proximity to road surfaces. Samples collected within 5 meters of road edges shown contamination levels two to four times higher than those collected at 20 meters (Adesuyi et al., 2015). Chronic ingestion of these metals is linked to nephrotoxicity, neurodevelopmental disorders in children, and carcinogenesis (Patel & Kumar, 2025; Bhavani et al., 2024).

### 5.1.2 Polycyclic Aromatic Hydrocarbons (PAHs)

Polycyclic aromatic hydrocarbons (PAHs) are well researched chemicals in foods that have been found to exhibit mutagenic and carcinogenic potentials. PAHs are a class of compounds that result from the incomplete combustion of heating organic matter and their main characteristic is the presence of two or more benzene rings condensed in a structure (Mafra et al., 2021). These lipophilic compounds adsorb onto the surface of oily seeds (e.g., melon, sesame) and porous tubers, posing long-term cancer risks. Open sun drying is recognized as "safe havens" for environmental pollutants such as heavy metals and polycyclic aromatic hydrocarbons (PAHs) from vehicle exhaust, tire and brake wear, and biomass smoke, all of which are toxic and potentially carcinogenic (David et al., 2019). In addition, sun drying on concrete, rock and asphalt surfaces can transfer natural radionuclides ($^{40}K$, $^{238}U$, $^{232}Th$) into foods such as cassava flour, increasing ingestion radiation dose above that from products dried on elevated fabric surfaces (Oyero et al., 2024).

### 5.1.3 Volatile Organic Compounds (VOCs)

Products dried openly along roadside can be contaminated by benzuene, toluene and xylene from vehicle exhausts, particularly crops with high surface area to volume ratios like shredded vegetables and spices (Faber et al., 2013).

### 5.2 Microbial Contamination: Microbes, Mycotoxins, and Vectors

The primary food safety concern associated with open sun drying is microbial contamination, which occurs through several medium. Commodities spread on bare ground are exposed to soil-borne microorganisms including pathogenic bacteria such as Salmonella spp., *Escherichia coli O157:H7*, *Listeria monocytogenes, Bacillus cereus,* and *Clostridium spp.,* etc. (Dauda et al., 2022). Dust and aerosols generated by moving vehicle and wind carry microbial loads onto drying surfaces, while insects (particularly flies), cockroaches, and beetles may act as mechanical vectors, transporting pathogens from faecal matter, decaying organic material, and sewage to food surfaces (Patel et al., 2022; Noda et al., 2023).

### 5.2.1 Pathogenic Microorganisms

Dust and soil particles carried by wind deposit fecal coliforms, *Salmonella spp*., *Shigella spp*., and *Staphylococcus aureus* onto moist food surfaces. The slow drying rates during cloudy periods or at night allow these pathogens to proliferate rather than being inactivated by heat (Alp & Bulantekin, 2021; Omorodion & Obiobu, 2025).

### 5.2.2 Mycotoxin Proliferation

Mycotoxins is a toxic secondary metabolite produced by filamentous fungi, usually *Aspergillus, Fusarium* and *Penicillium* species, are one of the deadliest food safety consequences of inadequate drying in Nigeria (Adeyeye, 2016; Gurikar et al., 2023).

Aflatoxins, produced primarily by *Aspergillus flavus* and *Aspergillus parasiticus* are potent hepatotoxins and carcinogens classified by the International Agency for Research on Cancer (IARC) as Group 1 human carcinogens (Ahmad et al., 2022; Gemede, 2025). Fumonisins, which is produced by *Fusarium verticillioides* are associated with esophageal cancer and neural tube defects. Ochratoxin A, deoxynivalenol and zearalenone are as well associated with chronic health effects (Magembe, 2025; Kaur et al., 2026). The diurnal cycle of drying (day) and rewetting (night dew) extends the time food remains in the critical water activity range (0.70 < aw < 0.85) conducive to fungal growth (Tapia et al., 2020). This promotes the proliferation of *Aspergillus flavus, A. parasiticus,* and *Fusarium verticillioides,* thereby producing aflatoxins and fumonisins, respectively. Aflatoxin B1, a Class 1 human carcinogen linked to hepatocellular carcinoma, is frequently detected in roadside-dried maize and groundnuts at levels >20 ppb, violating Nigerian and international regulatory standards (Afolabi et al., 2015; Iyto et al., 2021).

The prevailing occurrence of mycotoxin contamination in Nigerian commodities is increasingly alarming. Ifeji et al. (2014) assessed aflatoxin and ochratoxin A (OTA) contamination in 81 raw and roasted groundnut samples from four microclimatic zones of Niger State, Nigeria. AFB1, AFB2, and OTA were detected in 88.9%, 75.3%, and 90.1% of samples respectively, with AFB1 concentrations reaching as high as 188 µg/kg. All aflatoxin-positive samples exceeded the Nigerian and EU regulatory limit of 2 µg/kg for AFB1, while 55% of samples surpassed the 5 µg/kg OTA regulatory limit.

Magomya and Mbatsav (2023) also assessed AFB1 contamination in groundnut and maize samples from Wukari, Nigeria, finding AFB1 present in all samples, with 90% exceeding the allowable limit of 5 µg/kg. Concentrations ranged from 7.79–14.08 µg/kg in groundnuts and 1.48–15.50 µg/kg in maize. Chronic daily intake values were notably higher in children than adults for both food types, indicating greater vulnerability in younger consumers. Margin of exposure (MOE) values were far below the recommended ≥10,000 threshold, signifying a high carcinogenic risk to consumers. These contamination levels have direct implications for both domestic consumer health and Nigeria's agricultural export competitiveness.

### 5.2.3 Zoonotic and Vector-Borne Risks

Rodents, birds, and insects are attracted to exposed grains and fruits. Rodent urine and feces can transmit Lassa fever virus and Leptospira bacteria, while insects like houseflies act as mechanical vectors for enteric pathogens (Olagunju, 2022). Infestation by storage pests (e.g., *Sitophilus zeamais, Prostephanus truncatus*) often begins in the field during drying, leading to significant quantitative losses before storage even commences (Demis & Yenewa, 2022).

## 5.3 Physical Contamination and Handling Related Risks

Physical contamination from sand, grit, animal hair and droppings, glass, plastic fragments, and insect body parts is a main consequence of open surface drying (Adeyeye, 2022). Though not invariably causing acute illness, physical contaminants reduce product quality, create consumer rejection and can cause choking or dental injury, particularly when grain-based products are consumed by children (Shehu et al., 2018). Insects (weevils, moths, houseflies, and blowflies) attracted to drying food not only physically contaminate the product but accelerate moisture reabsorption through metabolic activity, further compromising drying quality (Jespersen, 2003). Uncontrolled human handling during turning, trampling and collection further increases risks (Baidhe et al., 2024; Alp & Bulantekin, 2021).

## 5.4 Public Health Implications

Food contamination from inadequate processing, preservation and storage is estimated to contribute to hundreds of thousands of food poisoning deaths annually in Nigeria, with open sun drying identified as a major contributing practice (Adenitan et al., 2022; David et al., 2019).

Although many roadside dryers recognize the possibility of exhaust contamination, they are largely unaware of the chronic health hazards associated with heavy metals, PAHs and mycotoxins and continue to dry products both for sale and household consumption (Bolade, 2016; David et al., 2019). The convergence of these hazards creates a synergistic health burden, especially where consumption is frequent and regulation weak (Adenitan et al., 2022; Bolade, 2016; David et al., 2019; Oyero et al., 2024; Baidhe et al., 2024; Adeyeye, 2016; Alp & Bulantekin, 2021). For example, heavy metals can suppress immune function, making consumers more susceptible to infections from co-occurring pathogens. Similarly, mycotoxins can impair liver detoxification pathways, exacerbating the toxicity of ingested PAHs and heavy metals. Vulnerable populations, including children, pregnant women, and immunocompromised individuals, are at heightened risk of acute poisoning and chronic degenerative diseases from consuming contaminated roadside-dried foods.

## 6. Solar drying technologies

Solar drying has evolved from simple sun exposure to a diverse family of engineered systems designed to dehydrate foods efficiently, hygienically and with minimal fossil energy use (Ade et al., 2018; Behera et al., 2022; Kamarulzaman et al., 2021). Unlike passive open sun drying, solar dryers provide a semi-controlled or fully controlled environment that shields produce from environmental contaminants while enhancing drying kinetics through forced or natural convection (Fernandes & Tavares, 2024). The fundamental operating principle relies on the greenhouse effect: short-wave solar radiation penetrates a transparent glazing (glass or polycarbonate), is absorbed by a dark absorber plate or the produce itself, and is re-emitted as long-wave infrared radiation that is trapped within the insulated chamber, raising internal temperatures by 15–35°C above ambient (Oyewole et al., 2023; patel et al., 2024; Joel et al., 2024).

### 6.1 Principles of Solar Drying

Improved solar drying technologies harness the same fundamental energy source as open sun drying but do so through engineered systems that control temperature, airflow, humidity, and exposure to contaminants. The fundamental principle involves converting solar radiation to thermal energy within a collector system and directing this energy to reduce the moisture content of food commodities placed within a protected drying chamber (Jangde et al., 2022). By enclosing the drying environment, solar dryers achieve higher drying temperatures, lower relative humidity within the drying space, faster and more uniform drying, and complete protection of commodities from rain, dust, insects, and other contamination vectors (Ade et al., 2018; Ajao et al., 2025; 2026).

The theoretical advantage of solar dryers over open sun drying rests on psychrometric principles: the ability to raise air temperature by 10–20°C above ambient within the collector, which simultaneously reduces relative humidity by 30–50%, thereby increasing the vapor pressure deficit and thus the driving force for moisture removal from food (Kiritkumar, 2026). Increased temperatures within properly designed solar dryers can also achieve pasteurization-level surface temperatures (55–70°C) that reduce pathogenic microbial loads, a benefit not achievable in open sun drying (Owureku-Asare et al., 2022).

### 6.2 Airflow Mechanisms and Efficiency

**6.2.1 Natural Convection (Passive):** Airflow is driven by buoyancy forces created by temperature gradients. Passive dryers are silent, require no electricity, and have minimal maintenance needs, but offer limited control over air velocity, often resulting in longer drying times (Ade et al., 2018; Oyewole et al., 2023).

**6.2.2 Forced Convection (Active):** Photovoltaic (PV)-powered or grid-connected fans force air through the collector and drying chamber at velocities of 0.5–2.0 m/s. Active systems enhance convective heat and mass transfer coefficients, reducing drying time by 30–50% and improving product uniformity compared to passive designs (Rezaei et al., 2022; Mbakouop et al., 2023)

### 6.3 Classification of Solar Dryers

Globally, solar drying systems are categorized based on heat transfer mode, airflow mechanism, and integration with auxiliary energy sources:

**6.3.1 Direct (Greenhouse) Solar Dryers:** Produce is placed inside a transparent enclosure where it absorbs solar radiation directly. Airflow is driven by natural convection (chimney effect) or air vent or wind propelled. While simple and low-cost, direct exposure to UV radiation can degrade heat-sensitive phytochemicals like ascorbic acid and β-carotene (Ajao et al., 2025). Studies in Nigeria have documented consistent performance improvements of direct cabinet dryers over open sun drying. The primary limitations of direct solar dryers include the risk of overheating delicate products (since internal temperatures can exceed 70–80°C at solar noon), limited capacity per unit area, and the potential for condensation on the transparent cover to drip onto food, creating moisture pockets. For products sensitive to UV radiation such as orange-fleshed sweet potato and certain leafy vegetables, direct solar exposure within cabinet dryers can also cause pigment degradation and nutrient losses (Pagukuman & Wan Ibrahim, 2022).

**6.3.2 Indirect Solar Dryers:** These systems has the solar collector decoupled from the drying chamber. Air is heated in a separate flat-plate or evacuated-tube collector and ducted into an opaque drying chamber. This design prevents UV degradation, preserves product color and allows precise temperature control, making it suitable for high-value spices and medicinal plants (Deepak & Behura, 2023; Shekata et al., 2024)

**6.3.3 Mixed-Mode Dryers:** Combining direct and indirect principles, mixed-mode systems expose produce to both direct radiation and pre-heated air. This hybridization maximizes thermal efficiency and is particularly effective for high-moisture tubers and fruits (Mehta et al., 2022; Afzal et al., 2023).

**6.3.4 Hybrid Solar-Biomass Dryers:** To address solar intermittency, hybrid systems integrate biomass burners (using rice husk, corn cobs, or wood waste) or thermal energy storage (TES) materials like phase-change materials (PCMs) and pebble beds. These systems enable 24-hour operation, reducing total drying time by 40–60% compared to pure solar systems (Pawar et al., 2024; Anyaoha et al., 2025).

Across these types, performance depends on solar irradiance, air temperature and velocity, dryer geometry, loading, and product characteristics (Deepak & Behura, 2023; Fernandes & Tavares, 2024).

## 7. Food safety benefits of solar drying technologies

The transition from roadside open sun drying to solar drying technologies represents a critical control point intervention in the Nigerian food value chain. By enclosing the drying process within a controlled thermal and physical environment, the dryer systematically mitigate the chemical, biological and physical hazards inherent to roadside practices. Empirical evidence from recent Nigerian studies demonstrates that solar dryers not only accelerate moisture removal but also fundamentally alter the safety profile of dried commodities, reducing toxicant loads and ensuring compliance with national and international food safety standards (Adenitan et al., 2021; Joel et al., 2024; An-nori et al., 2022; Oni et al., 2022; Kiritkumar, 2026).

### 7.1 Mitigation of Chemical Contaminants

The enclosed design of solar dryers physically isolates and prevent produce from the polluted roadside microclimate, preventing the deposition of vehicular exhaust, dust and hydrocarbon residues.

7.1.1 Exclusion of Heavy Metals: In the roadside sun drying, where produce is directly exposed to traffic emissions, meanwhile the solar dryers utilize filtered air intakes and sealed chambers that prevent the accumulation of heavy metals such as lead (Pb), cadmium (Cd), nickel (Ni), and chromium (Cr). Studies has established that solar-dried grains and vegetables contain heavy metal concentrations below the Codex Alimentarius detection limits (<0.01 mg/kg), whereas roadside-dried counterparts mostly exceed permissible safety thresholds by 2–5 fold (Kaimal et al., 2022; Adenitan et al., 2022).

7.**1.2 Prevention of PAH and Hydrocarbon Deposition**: The opaque or UV-stabilized transparent walls of solar dryers block the ingress of polycyclic aromatic hydrocarbons (PAHs) and volatile organic compounds (VOCs) from vehicle exhaust. This is particularly critical for oily seeds (e.g., melon, sesame) and porous tubers that readily adsorb lipophilic toxins during open sun drying (David et al., 2019; da Silva Junior et al., 2022).

7.**1.3 Elimination of Asphalt Contact**: By drying produce on raised, food-grade mesh trays within the chamber, solar dryers eliminate direct contact with bituminous surfaces, thereby preventing the migration of asphalt residues and complex hydrocarbon mixtures into the food (Olanipekun et al., 2025).

### 7.2 Suppression of Microbial Pathogens and Mycotoxins

The most significant food safety advantage of the solar dryer lies in their ability to rapidly reduce water activity (aw) to levels incompatible with microbial growth, while physically excluding vectors of contamination (Tapia et al., 2020; Alp & Bulantekin, 2021).

**7.2.1 Rapid Moisture Removal and aw Reduction:** Solar dryers achieve drying rates 30–50% faster than OSD, swiftly passing through the critical aw range (0.95–0.70) where bacterial and fungal proliferation is most active (Adenitan et al., 2022; Tapia et al., 2022). For instance, plantain chips dried in solar tent dryers reached a safe aw of 0.60 within 6 days, compared to 10 days for Open sun drying, significantly narrowing the window for microbial colonization (Adenitan et al., 2021).

**7.2.2 Thermal Inactivation of Pathogens:** Operating temperatures in solar dryers (45–78°C) exceed the thermal death point of many mesophilic pathogens. Total viable counts (TVC) in solar-dried spices and vegetables are consistently 2–4 log cycles lower than in open sun dried products. Specifically, Salmonella spp., E. coli and Staphylococcus aureus are rarely detected in solar-dried samples, whereas they are prevalent in 60–80% of roadside-dried counterparts (Hii et al., 2019; Adenitan et al., 2021; Joel et al., 2024; Owureku-Asare et al., 2022).

**7.2.3 Mycotoxin Prevention:** The combination of rapid drying, low final moisture content (<10%), and exclusion of nocturnal dew prevents the growth of Aspergillus and Fusarium spores. Critically, solar tent-dried plantain chips exhibited aflatoxin B1 levels of 3.2 ppb, compared to 18.7 ppb in OSD chips, with 80% of open sun dried samples exceeding the 20 ppb regulatory limit (Adenitan et al., 2021).

**7.2.4 Vector Exclusion**: Fine mesh screens (1–2 mm aperture) on air intakes and outlets physically block insects (flies, beetles), rodents, and birds, eliminating mechanical vectors for pathogens and preventing direct fecal contamination (Ade et al., 2018).

### 7.3 Elimination of Physical Contaminants

Solar dryers provide a physical barrier that ensures protection from external impurity contaminating the dried products. The UV covering makes the dryer an enclosed structure thereby preventing deposition of road dust, sand and stones, which are ubiquitous in open sun dried products. This eliminates the risk of dental abrasion, gastrointestinal irritation, and the associated reduction in market value due to grittiness (Fathi et al., 2022; Fernandes et al., 2022). The enclosed feature of this dryer also exclude insect fragments, rodent hair, bird feathers, and plastic debris from degraded tarps. This ensures that dried products meet the physical purity standards required by regulatory bodies like NAFDAC and international exporters (Adenitan et al., 2021; Oguejiofor et al., 2022). Solar dryers are designed with removable, washable trays that facilitate hygienic loading and unloading, reducing cross-contamination risks associated with the manual turning and sweeping practices common in open sun drying (Joel et al., 2024; Oyewole et al., 2023).

### 7.4 Preservation of Nutritional and Phytochemical Quality

Quality preservation of nutritional composition as well as antioxidants benefits of food through drying are essential in enhancing the functional safety of such food which inferably affect health-promoting properties. Indirect and mixed-mode solar dryers shield produce from direct UV radiation, minimizing the degradation of light-sensitive nutrients. Telfairia occidentalis leaves dried in parabolic solar dryers retained 85–92% of Vitamin C and 78–85% of total phenolics, compared to 40–55% and 35–45% in open sun drying, respectively (Ikhajiagbe et al., 2021; Catorze et al., 2022; Ajao et al., 2026). Also, the color and sensory profile of solar dried products are preserved by preventing UV bleaching and oxidative browning, thereby preserving the natural color (e.g., redness in peppers, greenness in leafy vegetables) and aroma profiles, which are key indicators of product freshness and safety for consumers (Joel et al., 2024; Jangde et al., 2022; Ajao et al., 2026).

Shelf preservation of solar dried products are guaranteed as lower final moisture contents (4–8%) and water activities (<0.60) achieved in solar dryers inhibit enzymatic activity and non-enzymatic browning during storage, extending shelf life by 6–12 months compared to sun dried products (Islam et al., 2019; Adenitan et al., 2021).

### 7.5 Regulatory Compliance and Market Access

The hygienic superiority of solar-dried products directly meets regulatory compliance and enhanced market opportunities. For instance, solar dried products have consistently meet the microbial and chemical safety limits set by the National Agency for Food and Drug Administration and Control (NAFDAC) and the Standards Organization of Nigeria (SON), whereas open sun dried products frequently fail compliance tests due to high microbial loads and aflatoxin contamination (Ade et al., 2018; Adenitan et al., 2021; Joel et al., 2024). Aside compliance of the solar dried product to the local standards, they have also gotten access to the export market by meeting with the International market standards (FAO, EFSA, JECFA, CODEX, etc) set up for aflatoxins and heavy metals which are inaccessible to open sun drying producers (Ayeni et al., 2019; Adenitan et al., 2021; 2022; Fortin, 2023; Ocagli et al., 2024).

## 5. Conclusions

Roadside open sun drying remains a deeply entrenched drying practice in Nigeria, driven by poor economic state, cultural tradition, low or no capital intensity and absence of affordable alternatives among smallholder farmers and rural food processors. However, this review has demonstrated that the practice generates a complex array of chemical, microbial and physical food safety hazards including dust, animal droppings and debris altering the quality and acceptability of the dried products. In addition, heavy metals accumulation, aflatoxin contamination and volatile compounds exceeding regulatory limits, as well posing health concerns on Nigeria consumers.

The proliferation of pathogenic bacteria and ubiquitous impurities are not excluded as a causable risk in public health. The solar drying technologies offer a technically credible and appropriate solution, consistently demonstrating lower contaminant loads, faster moisture removal, and regulatory-compliant product quality that meets both local and international food safety standards.

Several research works have been carried out on the development of solar dryers in the last decade and beyond, yet adoption remains constrained by cost, limited awareness, and weak policy enforcement. Transitioning from roadside open sun drying to improved solar drying systems is therefore not merely a technical upgrade but a necessary public health intervention for Nigeria's food system.

Bridging this gap requires more than just better technologies but good policy support, subsidies for local manufacturing and public health awareness to ensure that Nigeria's food system no longer compromise its future well-being.

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