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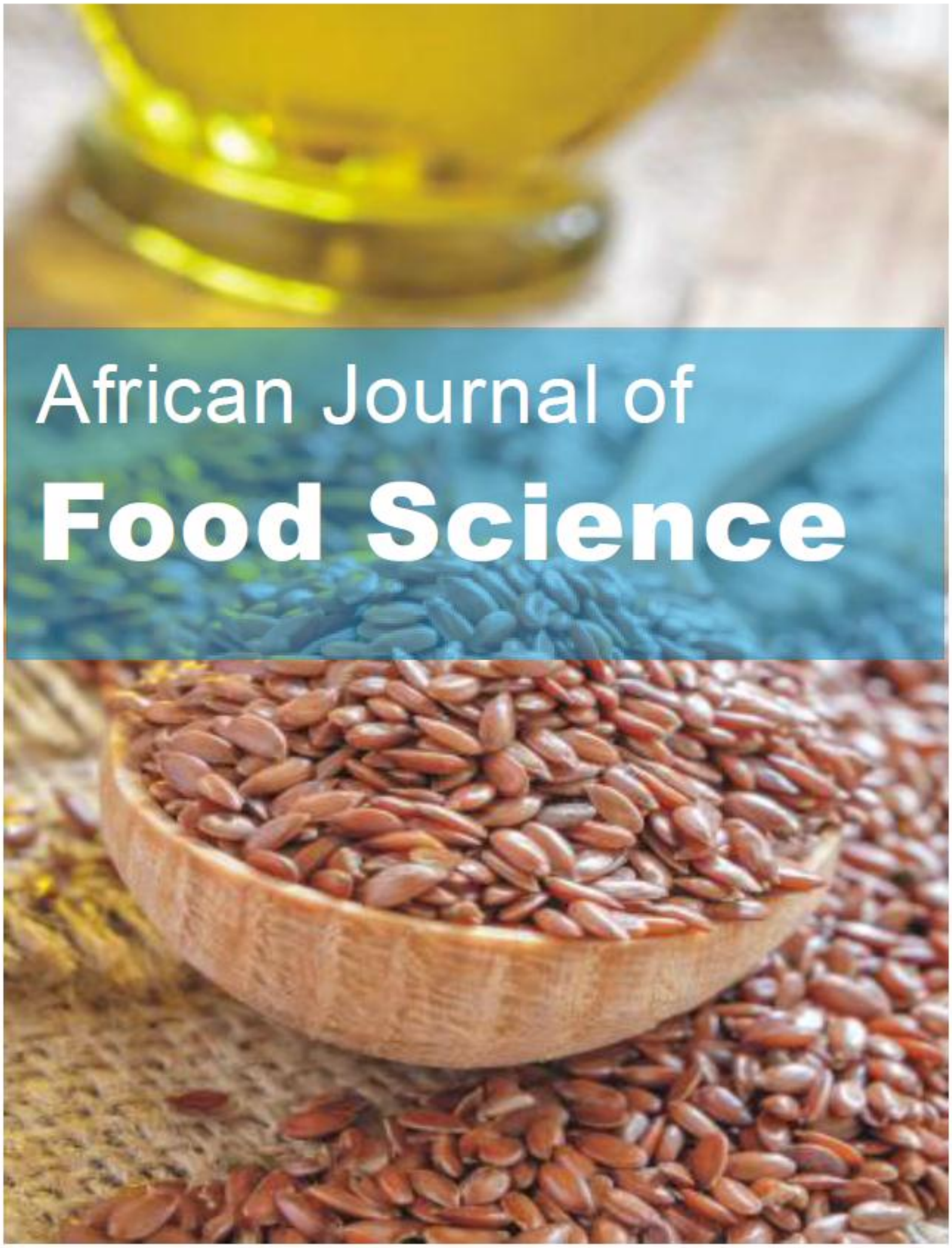

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African Journal of Food Science

Full Length Research Paper

Evaluation of aflatoxin B1 contamination of peanut butter in The Gambia

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Aflatoxins are poisonous, mutagenic, and carcinogenic compounds produced by *Aspergillus* fungi that contaminate various agricultural produce and products including peanut butter. Peanut butter is among the most consumed recipe in The Gambia. Thus, a cross-sectional assessment was conducted to evaluate the levels of aflatoxin contamination in processed peanut butter, sold and consumed locally in the country. In total, 85 peanut butter samples of approximately 2.0 kg each were bought at random within the six administrative regions across the country. All the samples were analyzed for aflatoxin contamination using thin layer chromatography (TLC) technique. Aflatoxin B1 was detected in 8 (9.4%) of the samples and only one (1.20%) of the samples exceeded both the Codex Alimentarius Commission and FAO/WHO Food Standards Program of 15 μg kg^{-1}. Likewise, only 5 of 85 samples representing 5.90% exceeded the European Union maximum limits for total aflatoxin of 4 μg kg^{-1} in peanut and processed products intended for direct human consumption. The remaining samples (77 of 85) representing 90.6% were negative or without any detectable aflatoxins. The analyzed samples therefore indicate that majority of peanut butter especially homemade is safe for human consumption.

Key words: Aflatoxin B1, peanut butter, thin layer chromatography (TLC), The Gambia.

INTRODUCTION

Several agricultural produce are susceptible to fungal attack that produces toxic metabolites referred to as mycotoxins. Aflatoxin is a food or grain-borne toxic secondary metabolites produced by the fungi *Aspergillus flavus* and *Aspergillus parasiticus*. These fungi can infect a wide variety of crops such as corn, groundnut, cottonseed, tree nuts, etc., either in the field or during post-harvest (Horn, 2005; Miningou et al., 2021). Spores if not atoxigenic of *A. flavus* are saprophytic in nature and once they become pathogenic, they are known to produce an array of toxic secondary metabolites including aflatoxins (Nallathambi and Umamaheswari, 2009).

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Infestation by the fungus can occur on these produce even during processing, handling, storage or transportation (Nakai et al., 2008). Both raw and processed products are highly susceptible to mycotoxin contamination including milk and vegetables (Giryn and Szteke, 1995).

Aflatoxins have become a concern in agriculture, trade, animal and human health on a global scale (Bennett and Klich, 2003). Aflatoxin B1 (AFB1) is known as a potent hepatocarcinogen and can play a synergic action with hepatitis B or C viral infections leading to hepatocellular carcinoma (HCC) (Turner et al., 2000; McKean et al., 2006; Groopman et al., 2008; Eaton and Groopman, 2013).

Aflatoxin B1 is strongly linked to immune-system suppression, increased susceptibility to diseases, and growth retardation, notably stunting (Henry et al., 1999; Gong et al., 2002; Turner et al., 2003; Williams et al., 2004). Reports have shown that high exposure to aflatoxin causes infertility, abortions, and delayed onset of egg production in birds (Oladele, 2014). Furthermore, loss of appetite, skin discoloration, and even yellowish pigmentation on skin can be observed in fish. This hazardous toxin can be transformed to aflatoxin M1 when feeds of livestock are contaminated (Carvajal et al., 2003; Mohammadi, 2011). In The Gambia, groundnut is the main cash crop of the country and peanut butter is among the most consumed product in the country. Aflatoxin impact on international trade resulting from price losses and rejected exports is detrimental to the economy of the country. It has been reported by Joseph Ndenn, Iris Consulting (2018) that an average price loss per annum sums to US$1.5 M (2000-2014) and an average annual loss from rejected exports adds US$62,854 (2012-2015).

The Gambia is a tropical country with a sahelian climate; defined by a long dry season (November- May) and a short wet season (June-October). The country has an average monthly temperature range of 18 to 30°C during the dry season and 23 to 33°C during the wet season. The average monthly relative humidity varies from 68 to 70% during the dry and wet season, respectively, and the average rainfall ranges from 800 to 1200 mm (GOTG, 2020). These climatic conditions provide the optimum environments for the growth of the *Aspergillus* fungus. Improper agricultural practice like continuous cropping, late weeding, poor drying and storage of nuts with mechanical damage, coupled with low humidity, drought, insect, crop genotype, and soil condition can increase crop susceptibly to aflatoxin (Leszczynska et al., 2000).

Groundnut and its product, peanut butter are considered nutritious, as they contain proteins, oils, fatty acids, carbohydrates, and minerals (Settaluri, 2012). This, ironically, makes them a rich medium for fungal growth and aflatoxin contamination (Barberis et al., 2012). A 100 g roasted peanut is said to constitute 1.55 g of water, 21.51 g of carbohydrates, 8.0 g of fiber, 9.66 g of lipids (fats), 23.68 g of proteins and a total calories of 2448 kJ (585 kcal) (USDA, 2011). Peanut and its additives could provide such a nutritious diet to satisfy WHO recommended average requirement of 0.66 g of protein per kg of ideal body weight, and a "safe level" of 0.86 g/kg of body weight (Food and Nutrition Board, 2002).

Peanut butter locally referred to as "*De gay*", is made from roasted groundnut at high temperature (160°C) (Siwela et al., 2011), blanched, deskinned and ground to paste after salt being added as a stabilizer (Peanut Institute, 2012). "*De gay*" is the primary recipe for a popular soup called "*domoda*" across all socioeconomic or demographic status in The Gambia. The stew is consumed nationwide due to its relative affordability and organoleptic properties.

Frequent deaths especially in children are repeatedly reported in many sub-Saharan countries due to malnutrition. Groundnut, a rich source of protein containing essential amino acids, can help in preventing malnutrition (Sanghvi and Murray, 1997).

Schroder et al. (2004) reported that people more adherent to a traditional Mediterranean diet, which includes nuts, had statistically lower body mass index (BMI). And a US food survey data revealed that peanut eaters have lower BMIs than non nut and peanut eaters (Sabate, 2003; Griel et al., 2004).

Peanut butter contains beneficial mono and poly unsaturated fats and is rich in antioxidants, vitamin E and the polyphenol, p-coumaric acid and help to lower blood cholesterol levels, reduce risk of heart disease by 50% (Talcott et al., 2005). The β-Sitosterol (phytosterol) is an anti-cancer compound found in peanut and peanut butter (Lee et al., 2004).

Virtually no scientific data exists on aflatoxin contamination of peanut butter in The Gambia. Considering the wide consumption rate of "*domoda*" and the need to ensure food and public health safety, the study is designed to probe the occurrence and prevalence of aflatoxin in peanut butter nationwide.

MATERIALS AND METHODS

Peanut butter sampling

About 2 kg of 85 samples of peanut butter were incrementally collected using multistage sampling method for markets and homes, while purposive sampling for production areas or processors within the six administrative regions in The Gambia (Figure 1). A total of 20 samples from the Greater Banjul Area (GBA) which include the Kanifing Municipality, 15 samples from West Coast Region (WCR), North Bank Region (NBR) and Upper River Region (URR), while 10 samples from Lower River Region (LRR) and Central River Region (CRR) (Table 1). With respect to sample Collection Points (CP), 36 samples were taken from homes, 30 market samples and 19 samples from processors (Table 1). All the samples were kept in zip bags, and kept in a quart cooler then transported to the Food Chemistry Laboratory at the National Agricultural Research Institute (NARI) for aflatoxin contamination analysis.

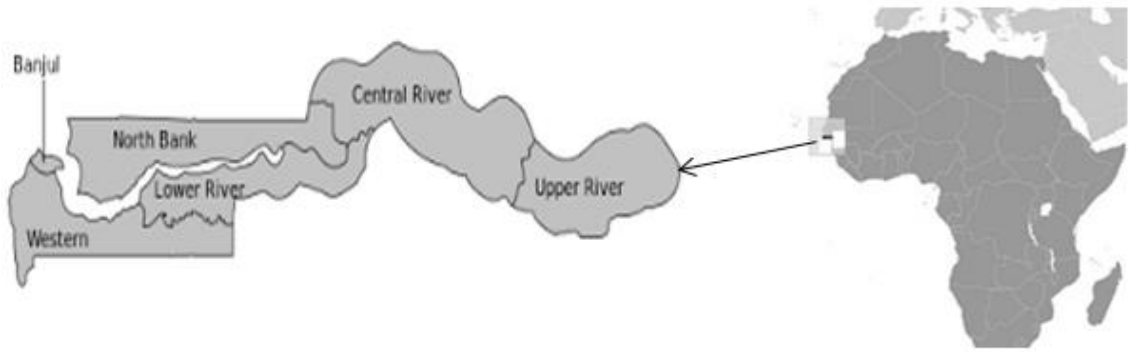

Figure 1. Map of The Gambia with demarcated sampling regions.

Table 1. Samples distribution in homes, markets and processors within regions.

Collection points (CP)/ regions	GBA	WCR	LRR	NBR	CRR	URR	Grand total
Homes	3	3	5	10	5	10	36
Market	10	8	3	3	3	3	30
Processors	7	4	2	2	2	2	19
Total	20	15	10	15	10	15	85

Extraction of aflatoxin

A 100 g representative sub-sample was obtained from each 2 kg sample and blended with 300 ml of distilled H_2O into slurry. A 100 g slurry was blended for 3 min with 250 ml methanol, 100 ml hexane and 2 g of NaCl, filtered using a Whatman filter paper of 32 cm and 50 ml collected. Exactly 150 ml of distilled water was poured in a separating funnel then the 50 ml filtrate and 25 ml of chloroform were respectively added and the separating funnels topped then slightly shaken. When separation settled, elutes were collected in a small beaker containing 2 anti-bumping granules for calm boiling then heat to dryness in a steam bath. The dried beaker was allowed to cool and about 5 to 8 ml chloroform pipetted to it, a dropper was used to rinse its wall to cleanse off any aflatoxin then the chloroform was subsequently filled in a vial containing 2 anti-bumping granules. The vials were evaporated to dryness using an electric vial-rack heater. After dryness and the vials cooled, a 0.25 ml of benzeneacetonitrile (98:2 v/v) solution was pipetted into them and vortexed.

Reading of TLC plates

Samples were spotted using an assipettor-fix for (5-10-40 µl), respectively on the TLC silica gel coated glass plates of 20 cm × 20 cm and thickness layer of 0.25 mm against the standard (1-3-7-10-15-20 µl) labeled using a pencil on top of the plate. The TLC plate is gently lowered in an already loaded tank with diether: methanol: water (94:4.5:1.5 v/v) positioned on a flat surface and covered with the lid. After about 45 to 60 min, when the plate in the tank had absorbed the solvent and at three-quarter length of the plate, the plates were removed and allowed to dry up for about a minute then illuminated below the TLC machine or lamb and viewed under long-wave of UV 366 nm in the dark room. The fluorescence intensities of aflatoxin B1 spots in samples were compared to the respective spots of standard in terms of color and retention factor (R_f). Aflatoxin B2, G1, and G2 spots were compared by the same procedure. Both preparation of the standards and the calculation of aflatoxin B1 concentration were done as stated by Jallow et al. (2019) in part per billions.

Statistical analysis

Data were statistically analyzed using SigmaPlot 12, applying t-test ($P<0.05$) for pairwise comparisons.

RESULTS

The data indicated that aflatoxin contamination in peanut butter is generally low in the country. There was no significant differences ($p>0.05$) among regions (Table 2) not at collection points (Table 3). Aflatoxin was not detected in 77 (90.59%) of the 85 samples analyzed (Table 2). Furthermore, there were no detectable aflatoxin in all the peanut butter samples collected from the GBA and NBR, therefore those regions are regarded as aflatoxin contamination free zones under this study (Figure 2).

Out of the 15 samples from WCR, only two (2) samples (13.33%) were contaminated with aflatoxin by 2.91 and 38.76 ppb of aflatoxin. While from the 10 samples of LRR, only one (1) sample (10%) was found to have been contaminated with aflatoxin with 2.91 ppb of aflatoxin. CRR and URR both registered 20% of aflatoxin contamination of the 10 and 15 samples analyzed, respectively. The two (2) contaminated samples from

Table 2. Aflatoxin B1 concentration of peanut butter samples from the six regions of The Gambia.

Region	No. of samples	AF-positive samples, *n* (%)	Range of contamination (ppb)	Mean of contamination (ppb)	SD (±)	CV (%)	LSD
GBA	20	0 (0)	ND	ND	0.00		
WCR	15	2 (13.33)	ND - 38.76	2.78	9.98		
LRR	10	1 (10)	ND - 2.91	0.29	0.92		
NBR	15	0 (0)	ND	ND	0.00	23.60	2.82
CRR	10	2 (20)	ND - 12.60	2.23	4.74		
URR	15	3 (20)	ND - 7.26	0.84	1.92		
Total	85	8 (9.41)					

ND= Not detected; ppb= parts per billion, SD = standard deviation, CV= coefficient of variation, Lsd=less significant difference.

Table 3. Aflatoxin B1 concentration of peanut butter samples from the collection points (CP).

CP	No. of sample	No. of positive samples, n (%)	Range of contamination (ppb)	Mean	SD	CV (%)	LSD
Homes	36	2 (5.56)	ND - 2.91	0.61	0.67		
Markets	30	4 (13.33)	ND - 38.76	1.71	7.14	29.40	3.87
Processors	19	2 (10.53)	ND - 12.60	1.17	3.54		

CRR recorded 12.60 and 9.65 ppb, while 2.91, 6.74 and 7.26 ppb from URR. Out of the total samples (85) analyzed, only eight (8) samples (9.4%) were found to have contaminated aflatoxin B1. Only 1.20% (1 of 85) of samples in WCR at the Collection Point “Homes” Table 3 with 38.76 ppb exceeded both the Codex Alimentarius Commission, Joint FAO/WHO Food Standards Program of 15 µg/kg (ppb) intended for further processing (Codex Alimentarius Commission, 2001). Furthermore, only 5.90% (5 of 85) samples exceeded the EU maximum limit for total aflatoxins of 4 µg/kg (ppb) for groundnut, nuts, and processed products intended for direct human consumption or use as an ingredient in foodstuffs (EU, 2010). Only 1.20% (1 of 85) of samples exceeded all international acceptable limits with 38.76 ppb (Table 2).

A 42.35% were collected from homes, 35.29% from markets and 22.35 from processors (Table 3), two (2) came out positive for both homes and processors 5.56 and 10.53% and 4 samples (13.33%) from the markets (Figure 3).

DISCUSSION

These finding reports the level of aflatoxin contamination in peanut butter samples processed and consumed in The Gambia. The negative results of the peanut butter in the GBA which is mostly supplied from NBR could be as a result of the frequent and quick completion of peanut butter consignments sale due to the high demand of the densely population of the area (about 20% of the country’s population). In the same light, a 5 km ocean separates GBA from NBR, a region known as the most peanut grown hub. Consequently, the farmers in this agro-ecological zone (sudano-sahelian) are more experienced in good agronomical practices that mitigate aflatoxin in groundnut and practice proper post-harvest like drying, sorting and screening, thus the negative results. And unlike GBA, most consumed peanut butter is homemade in NBR.

Similar results were reported by Azer and Cooper (1991) who analyzed 73 samples of peanut and peanut butter and found the contamination in only one (1) sample equal to 61 µg/kg. Again in Turkey, where only one peanut butter sample from a total of 85 peanut and peanut product samples had 2.0 ppb (Ozay, 1989). A 91% (10 of 11) peanut butter aflatoxin contamination with a mean 75.66 ng/g was found in Zimbabwe (Mupunga, 2014) and 27% (3 of 11) exceeds the EU maximum limits of 4 ppb. In Sudan, a range of 26.6 to 853 µg/kg in peanut butter was reported with 90% exceeding the EU maximum limit (Elzupir et al., 2011). This two African countries are known to be prone to drought and erratic rainfall. A survey conducted in Taiwan showed aflatoxins were detected in 10 out of 21 peanut butter samples, but the highest level of AFB1 was only 2.59 µg/kg (Ying-Chun et al., 2013). Also, higher total aflatoxin level was reported in Nepal with 42.5% (43 of 101) of aflatoxin contamination (Koirala et al., 2005). This might be due to high rainfall, hot and humid conditions that are prevalent in the Asian subcontinent.

Though consumption of aflatoxin susceptive crops most specifically peanut and it products has been identified as a strong risk factor for hepatocellular carcinoma (HCC). A

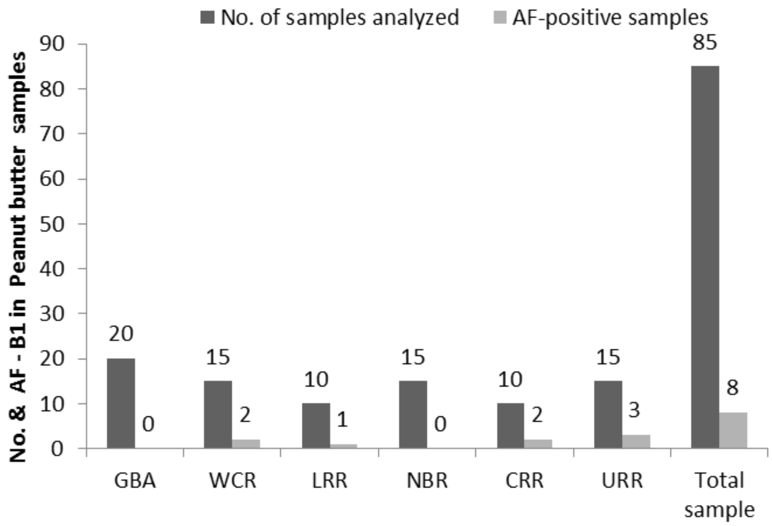

Figure 2. Aflatoxin contaminated samples at region.

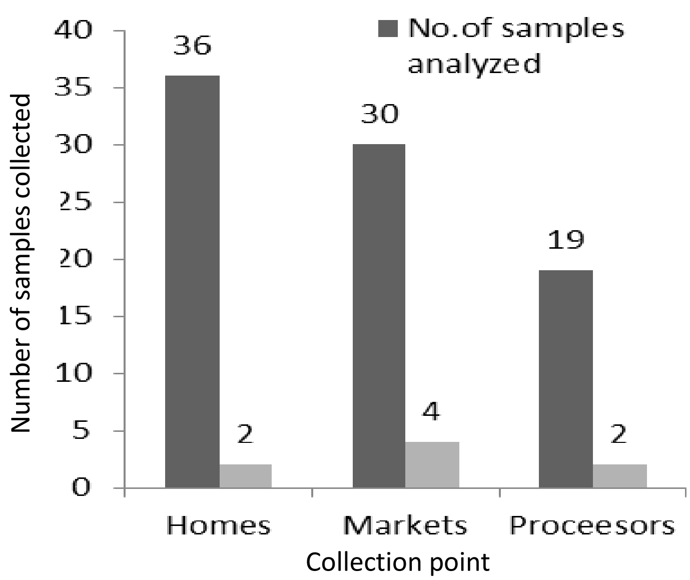

Figure 3. Aflatoxin contaminated samples at collection points.

report by PACA (2018d) revealed 285 liver cancer cases in 4 years in The Gambia.

Although, no established correlation was made to relate the cancer cases to the consumption of peanut and or its products or as a result of aflatoxin contamination. Other natural, environmental and habitual factors like, genetic makeup, exposure to hazardous chemical, smoking, alcohol, and underlying medical history may also be a factor to consider for the cancer cases. It is estimated that the risk of developing aflatoxin-induced liver cancer in The Gambia is 8.3 cases per 100,000 people. This is because of the HBV prevalence (15%) of the population (Gambia Aflatoxin Control, 2015). In The Gambia, HBV, HCV and aflatoxin exposure are known aetiologies of HCC with HBV accounting for a majority of cases. In a study, Bah et al. (2001) and Kirk et al. (2004) showed 10% cases of cancer were as a result of smoking**.** A Similar report indicates 57% of liver cancer cases in The Gambia are attributable to chronic hepatitis B infection (Kirk et al., 2006).

The low aflatoxin sequence of the CPs (Table 3) could be correlated to the shelf life of the product which might be as a result of the oil in it during production. Secondly, in the presence of phytoalexins, an inhibiting protein in seed for fungal colonization (Jallow et al., 2018) and time of sampling. Homemade peanut butter as expected, recorded the lowest contamination level. This is certainly because more precautionary measures like sorting the black and moldy and all foreign materials are done with precisions and much care is also given in its storage, since is purposely for home and family consumption. The product is transformed to soap if it loses one of its organoleptic features. Processors serve as the first and transitional points of the product, fewer and lower contamination are as a result of less time spent at this point before entering its finally stage. The market recorded the highest aflatoxin level which could be due to contrary practices to homemade and possible adulterations of the peanut butter to increase its volume for profit.

When proper food safety practices are maintained, this study confidently shows that the peanut butter consumed in The Gambia is safe, and therefore encourages the continuation of the consumption of this delicious and cultural stew "*domoda"* in order to gain the maximum health benefits. As stated by Kelly and Sabaté (2006), 37% lower from cardiovascular disease (CVD) and stroke for regular consumers of the product than those who do not at all. Furthermore, a water soluble vitamin (B9) known as folate or folic acid found in peanuts could help in human growth and aid the normal functioning of nerves and brain and may also help protect against cancers of the lung, colon, and cervix (Fishman et al., 2000).

Again these findings are substantiated with the attestation of a popular US TV talkshow called The Drs (2013), where a dietitian described this Gambian stew as a factor that may lower cancer risk. As a result the country is having one of the lowest cancer cases in the world. Epidemiological studies have confirmed that consuming peanut and its products, and snack food, at least four to five times per week may contribute to protect against, type two diabetes and gallbladder disease (Hu et al., 1998; Jiang et al., 2002; Tsai et al., 2004), weight management (Jennette, 2005), no positive correlation to increase body mass index (BMI) (Hu and Stampfer, 1999). The high protein and high unsaturated fat nature of peanuts may also contribute to the lack of weight gain associated with peanut consumption (Johnston, 2005).

Conclusion

The overall results demonstrate that 90% (77 of 85 samples) were not contaminated with aflatoxin. From the contaminated samples, eight (9.41%) sample exceeded the EU limits of 2 µg/kg (ppb) for aflatoxin B1 for direct consumption and only one sample exceeds the Codex Alimentarius maximum limits of 15 ppb. This study reassures the safety of peanut butter consumed in The Gambia, and therefore encourages the frequent consumption of this peanut butter stew in order to gain the maximum health benefits it had in it. And also recommends a national policy and regulatory document with budgetary allocations for aflatoxin management activities should be setup for the nation to redeem herself from the huge aflatoxin economic impact she is facing. A regular awareness creation and analytical surveillance programs be conducted by food control agencies and stakeholders is highly recommended to monitor the incidences of aflatoxin contamination in the country.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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Review

Technological advancements in the drying of fruits and vegetables: A review

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The aim of the review was to look into technological advances and methods for dehydrating fruits and vegetables, as well as the shortcomings of these methods and potential ways to improve them. All fruits and vegetables can be dried in various forms, including cuts, juice, paste, slurry, and even whole, using various dryers. Recent research on drying has focused on improving energy consumption/ efficiency, product recovery, and nutrient preservation. Technological advancements in drying methods involve development and optimization of novel drying techniques, including their combination to obtain quality products. As the demand for new and healthier ready-to-eat goods with lengthy shelf lives and greater rehydration capability expands, advancements in the drying of fruits and vegetables are crucial. The drying process has a tremendous impact on the product's quality and cost. New drying procedures may provide advantages such as enhanced energy efficiency, higher product quality, lower costs, and decreased environmental impact. Dehydration of agricultural products is a critical process that must be carried out with caution.

Key words: Dehydration, drying, fruits, technological advances, vegetables.

INTRODUCTION

Fruits and vegetables are the most commonly consumed super or functional foods (Rwubatse et al., 2014), yet their high moisture content (over 80%) makes them especially susceptible to bacteria that cause spoiling (Maisnam et al., 2017; Valarmathi et al., 2017). Keeping fresh is the best way to preserve the nutritional value of fruits and vegetables, but most storage methods necessitate low temperatures, which are difficult to maintain throughout the distribution chain. In contract, drying is an effective post-harvest management strategy, particularly in Nigeria and other Sub-Saharan African countries where power outages and rising fuel prices make low-temperature storage, handling, and distribution facilities scarce (Dereje and Abera, 2020). To improve

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their shelf life and increase food security, approximately one-fifth of the world's fresh produce are dried (Pragati and Preeti, 2014; Betoret et al., 2016; Feng et al., 2021). Dried fruits and vegetables make healthy eating more practical and can help close the gap between recommended and actual fruit consumption. By lowering water activity, dehydration keeps fruits and vegetables healthy and safe, prolonging their shelf life much beyond that of fresh produce. Drying processes also affects enzymatic behavior, sensory properties, and microbial growth (Özbek et al., 2007; Dereje and Abera, 2020).

Fruit and vegetable storage through drying has a long history and is based on sun and solar drying processes (Sagar and Kumar, 2010). Drying used to be as simple as lying the product out on mats, rooftops, or drying floors in the sun (Ahmed et al., 2013), using solar radiation and convective air. Other options include drying the harvest beneath a cover, on treetops, or even on field shelves (Rwubatse et al., 2014). Heat is transferred to the fruit or vegetable raw material through convection from the ambient air and radiation from the sun on its surface during sun drying. Since foods to be dried are exposed and climatic changes can occur, the method is highly unsanitary and volatile. Mechanized solar dryers such as tray, carbinet and tunnel dryers have been designed to overcome the challenges of damage, dust, pest infestation and unexpected rainfall encountered in open air drying (Pragati and Preeti, 2014; Rwubatse et al., 2014; Karam et al 2016; Ajuebor et al., 2017). Application of mechanized drying to conserve agricultural produce has grown significantly, necessitating the development of fast drying methods and approach that decrease the amount of fuel dispelled in these operations. It has been noticed that the aim of drying agricultural products has shifted. Previously, the goal was to lengthen the life span of dried fruits and vegetables, but now the goal is to produce high-quality dried vegetables and fruit (Rwubatse et al., 2014; Babu et al., 2018).

Presently, various drying methods are being utilized in equipment which may run on combustible fuels and/or electricity (Maisnam et al., 2017; Norhadi et al., 2020; Feng et al., 2021; Radojčin, et al., 2021). Convective drying within built-in structures is applicable to cabinet, tray and tunnel dryers (Mercer, 2014; Misha et al., 2013), with advances seen in fluidized bed drying (Law and Mujumdar, 2006). Drum dryers use conductive drying on heated surface in drying (Kerr, 2013). Fruit and vegetable juices have been dried and concentrated using atomization (Cal and Solohub, 2009; Mercer, 2014). Lyophilization, or the direct sublimation of ice to vapor, as well as the use of lower pressure in fruit and vegetable drying, result in products with improved rehydration, sensory properties, and drying times (Falade and Igbeka, 2007; Cenkowski et al., 2008). In explosion puff drying and low pressure super-heated steam drying, the concept of drying with steam and decreased vapor pressure is used. Not only is the drying time reduced, but the thermal efficiency is also improved (Calín-Sánchez et al., 2020). Due to the need to reduce energy losses during traditional hot air drying, heat pump drying systems were developed, which increase energy efficiency and reduce fossil fuel consumption (Fayose and Huan, 2016). Prior to drying, osmotic pretreatment of fruits and vegetables has been widely used to reduce processsing time and increase the overall consistency of the dried food product (Mehta et al., 2013). In addition, the use of electromagnetic waves in the drying of fruits and vegetables is rapidly increasing. The process involves the use of indirect electro heating (Marra et al., 2009) and vegetal products are dried in less time and at lower temperatures (Kahyaoglu et al., 2012; Nindo and Tang, 2007; Calín-Sánchez et al., 2020). However, technological advancements in the drying of vegetables and fruits, the process shortcomings, as well as potential ways to improve the process are reviewed.

ADVANCEMENTS IN THE DRYING OF FRUITS AND VEGETABLES

Drying fruits and vegetables has been practiced for ages and is dependent on sun and solar drying processes (Sontakke and Salve, 2015). The development of advanced drying technologies was prompted by low product quality and product contamination. Freeze, vacuum, osmotic, cabinet or tray, fluidized bed, spouted bed, Ohmic, micro wave, and combined and osmotic dehydration are the most frequently utilized drying methods (Pragati and Preeti, 2014; Maisnam et al., 2017; Tontul, and Topuz, 2017; Sakif et al., 2018). With the exception of freeze-drying and osmotic dehydration, the fundamental strategies for forcing water to vaporization during drying include conduction, convection, and radiation, with forced air being utilized to encourage vapor removal (Sagar and Kumar, 2010; Pragati and Preeti, 2014; Kumar and Belorkar, 2015). Drying methods can be broadly classified into traditional, mechanized and advanced methods of drying (Pragati and Preeti, 2014; Maisnam et al., 2017; Hasan et al., 2019).

Traditional methods of drying of fruits and vegetables

Sun drying is the oldest method of fruit and vegetable preservation (Misha et al., 2013). Solar energy, air, and a smokey flame have all been used to evaporate moisture from fruits, meats, cereals, and plants throughout history (Ahmed et al., 2013). Fruits are safe to dry in the sun because of their high sugar and acid content, but vegetables are poor in sugar and acid, rendering them unsuitable for sun drying. Fruits are placed whole or sliced in trays on elevated slabs and exposed to the open air until desired dryness is achieved. The best screens are stainless steel, teflon coated fiber glass or plastic. The optimum conditions for dying to occur are a minimum temperature of 86°F and a relative humidity of less than 60% (Ahmed et al., 2013). Low capital and operating costs, as well as the fact that little skill is required, are the key advantages of sun drying (Ahmed et al., 2013). One major drawback is that when the specific fruit ripens, optimal conditions for sun drying might not be sufficient. Insect infestation, dust and debris contaminants, longer drying time, direct exposure warming, quality degradation, and low rate of heat transmission owing to condensation of the evaporated moisture are only a few of the key concerns experienced when drying in the open air (Sontakke and Salve, 2015). This method can be used to dry raisins and plums.

Mechanized methods of drying of fruits and vegetables

Mechanical or electrical equipment is used to assist with artificial drying. Significant amounts of moisture may be extracted via artificial methods (Babu et al., 2018). Moreover, various parameters such as temperature, drying air flow, and drying time may all be controlled (Okoro and Madueme, 2004; Babu et al., 2018; Xiao et al., 2018).

Solar drying

Food is dried using solar dryers in the solar drying process. Solar dryers such as tray, cabinet, tunnel, spray and fluidized dryers are a form of convectional dryer in which the food is dried by air heated with sunlight energy and/or radiant energy absorbed by the food through a refractive medium, typically glass or polyethylene (Weiss, 2001; Alamu et al., 2010). While solar drying produces better product quality than sun drying, most solar dryers have a smaller capacity compared to open air drying. The process challenges include moisture condensation within the dryer and increased humidity as a result. There two types of solar drying such as direct and indirect solar drying (Figure 1). Food products such as berries, bananas, mangoes, and rosemary can be dried with solar dryers (Abhay et al., 2017).

Cabinet dryer

Fruit and/or vegetables to be treated are laid on shelves/racks within the drying chamber of the cabinet and blasted with hot dry air (Mercer, 2014). Although the equipment is inexpensive, the process is a batch operation with a high operating (labor) cost and low performance. Vital components of the dryer are depicted in Figure 2. Different models for potatoes chip, grapes, apricot and beans have been designed. A cabinet dryer designed for treating okra, chili pepper and plantain was fabricated and the performance evaluated by Ajuebor et al. (2017). The cabinet dryer performed optimally at the 70°C, relative humidity of 60%, and air speed of 3.0 m/s. At these values of the process parameters, drying time was shorter and of all the analysis carried out, the result obtained was better at this point.

Tray drying

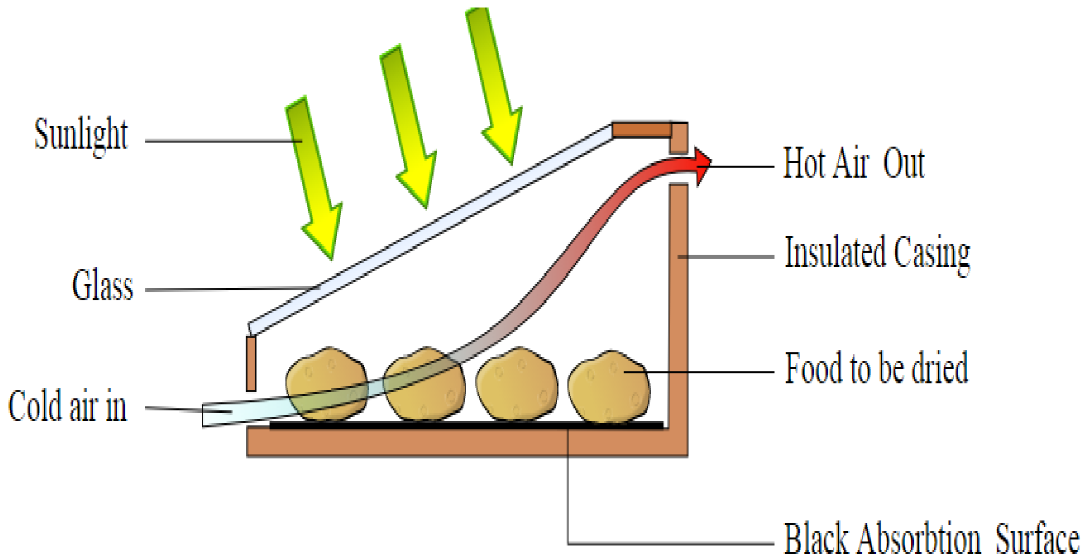
It is a batch dryer with a drying mechanism that is similar to a cabinet dryer. To optimize the amount of open space for air circulation, dried fruits and vegetables are arranged on large wire mesh trays (Figure 3). Once the trays have been loaded, they are placed on supports within a drying cabinet or compartment. After that, the drying chamber is sealed, and air is blown into it (Mercer, 2014). Uniform airflow distribution over the trays is critical to the tray dryer's performance (Misha et al., 2013). The tray dryer's major problem is uneven drying, which is caused by insufficient airflow circulation in the drying chamber. Solar energy is used in most of the dryer systems that have been built to lower operating cost (Misha et al., 2013). Colak and Hepbasli (2007) developed a model to dry green olives. This process can be used to dry apple, banana, and apricot slices. Because of the increased drying rate , improved product quality and appearance, the tray dryer was determined to be more effective than the oven dryer (Norhadi et al., 2020).

Tunnel dryers

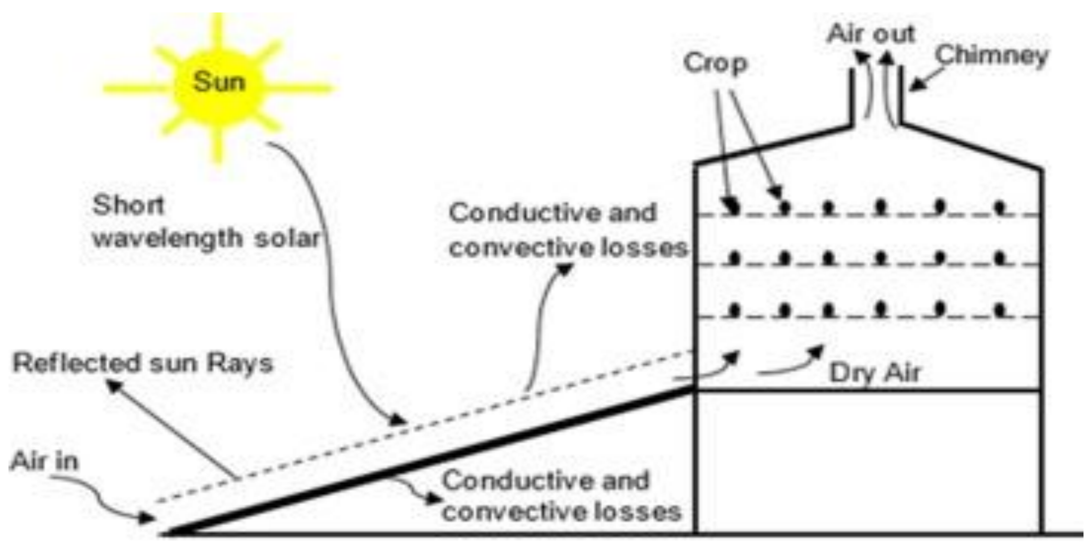
Considered an advancement of the tray and cabinet dryers, it was designed to replace sun drying of prunes with heated forced air dryer (Brennan, 2006). Tunnel dryers are long tunnels through which trucks transporting trays pass with or against a stream of drying air (co-current, counter current or mixed current). A truck carrying wet food enters one end of the tunnel, while another with dehydrated products exits the other end. The trucks are driven manually or mechanically (e.g., with the help of chains), depending on the scale of the trucks and the tunnel. Despite the flexibility of the drying method, tunnel dryers need significant amount of labor to run than a continuous belt dryer thus making it less widely utilised (Mercer, 2014). Apricots, peaches, pears, apples, figs, dates, and other fruits and vegetables have been dried using this process in the form of fragments, purees, and liquids.

Drum drying

A set of metal drums are heated with steam or hot water



A: Direct solar drying



B: Indirect solar drying

Figure 1. A schematic of a direct and indirect solar drying. Source: Adapted from: Abhay et al. (2017).

to the desired temperature. The food to be dried is introduced into the thin gap, or nip, between the drums as they rotate in opposite directions (Figure 4). This fruit or vegetable raw material must be in the form of a slurry or viscous liquid. The food sticks to the spinning heated drum's surface after passing through the nip, and moisture evaporates. Baked food is from the drum surface while rotation continues; using a doctor blade/ knife that continually skims the drum surface, extracting the dried materials (Mercer, 2014). The food can be applied to the drum surface in a number of ways (Kerr, 2013). The viscosity of the feed determines the feeding process. Drying parameters such as drying temperature, feed rate, rotation speed, feed concentration, and surrounding air condition influence the characteristics of drum-dried food such as particle size, bulk density,

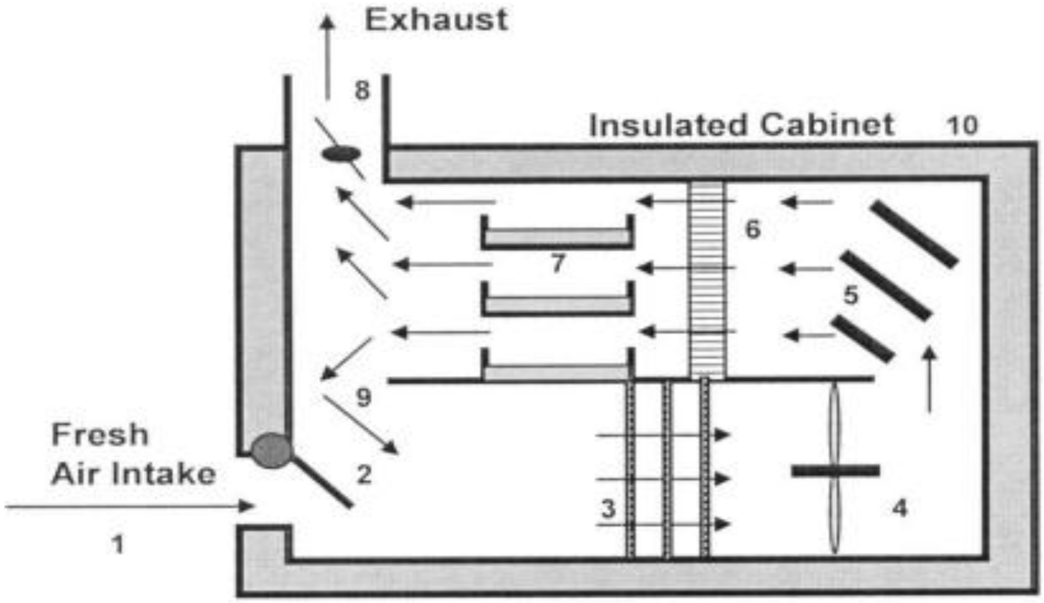


Figure 2. The components of a cabinet dryer. Source: Mercer (2014).
1 = Fresh air enters cabinet dryer, 2 = Adjustable damper allows fresh air and recirculation to be balanced, 3 = Heaters warm the air stream to the desired temperature, 4 = Adjustable fan conveys air and controls volumetric air flow-rate, 5 = Air distribution plates even out flow pattern of air, 6 = Screens filter particles from air and create back pressure, 7 = Product is contained in trays with heated air passing over them, 8 = Air is exhausted from cabinet dryer after removing moisture from products, 9 = Heated air with some drying capacity may be re-circulated, 10 = Cabinet is insulated to prevent excessive heat loss. The arrows indicate air flow.

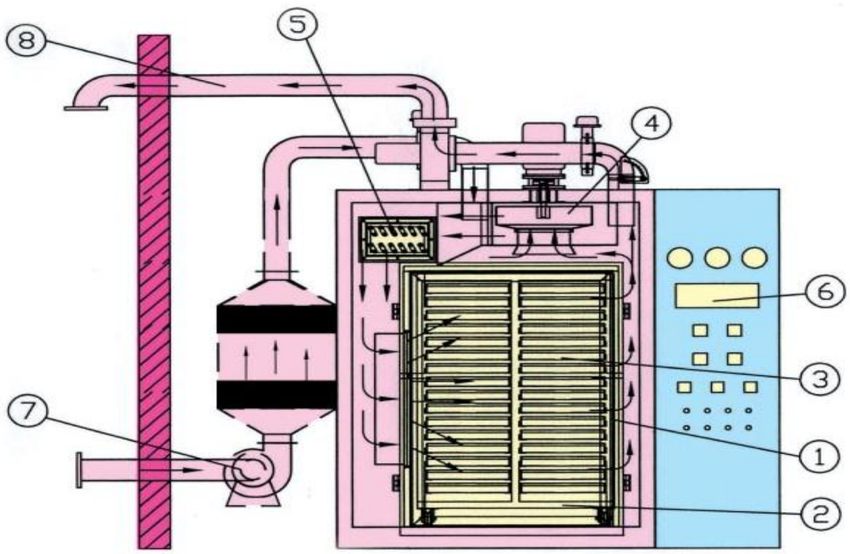
moisture content, and solubility (Nastaj, 2000; Pua et al., 2010). Cooked food flavor and non-enzymatic browning can result from heated surface drying. Heated surface drying may result in cooked flavor of the food and non-enzymatic browning. There is also difficulty in scraping-off sugar rich foods, high energy consumption of the process and hydration in the processing area due to condensation. The method has been used to transform mashed potatoes into dried flakes which can be used as instant mashed potatoes.

Spray drying

Cal and Solohub (2009), claim that the device was created to boost the drying and concentration of liquid substances by atomizing. Fruit or vegetable juice is blasted via an atomizing valve, resulting in small droplets that are equally spread throughout a vast drying chamber and allowed to fall into hot air flowing upwards (Mercer, 2014; Tontul and Topuz, 2017). Changes in parameters such as particle diameter, air temperature, and air speed, among others, can be used to accomplish the required degree of drying, so that when the droplets touch the bottom of the drier, they have devolved into small powder particles (Mercer, 2014). The technique may not be suitable for foods sensitive to mechanical damage, due to the strong shear action during atomization. Some drawbacks include the loss of bioactive compounds in the food and the stickiness of sugar-rich foods to drying equipment. In addition, the scale of the equipment and the cost of installation are also substantial. Tomato juice has been dried into powder using this method (Phisut, 2012; Verma and Singh, 2015).

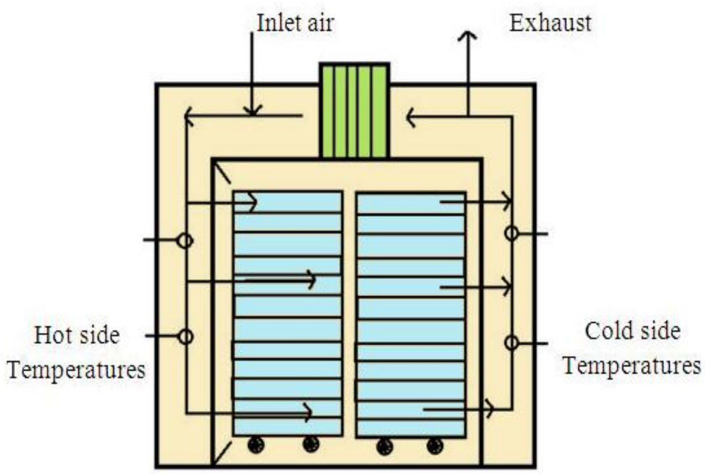
Fluidized bed dryers

The fact that the drying medium, which is usually warm air, comes into contact with all surfaces of the product being dried is recognized by fluidized bed dryers (Mercer, 2014). This drying method reduces the possibility of soluble material migrating by lifting the food particles and transporting them outside using heated air blown from beneath the bed. Through openings in the bottom, heated air is blown into the drying chamber. A linear velocity can be achieved by using a sufficient volumetric flow rate of air to lift the wet fruit or vegetable and keep it suspended in the air that is drying it (Mercer, 2014). The method is widely used to dry wet granular and particle food products that can be fluidized in beds of inert solids, such as slurries, pastes, and suspensions (Law and Mujumdar, 2006). The down sides of this method are particle size restrictions and poor thermal efficiency. Vegetables such as peas, green beans, carrots, and onion slices are commonly dried using this process (Kumar and Belorkar, 2015).



A: Tray dryer

1 = drying chamber, 2 = drying trolley, 3 = drying tray, 4 = circulation fan, 5 = Heat exchanger, 6 = control panel, 7 = fresh air inlet, 8 = exhaust damper.



B: Tray dryer working principle

Figure 3. Tray dryer and its working principle.
Source: Misha et al. (2013).

Advance methods of drying of fruits and vegetables

Various sophisticated drying techniques, including as solar, microwave, vacuum, infrared, freeze, oven drying, and various combination drying technologies, have been developed across the world and are effectively utilized for various fruits and vegetables (Hasan et al., 2019).

Freeze drying

Freezing the food, sublimating the ice, and extracting bound water molecules are all steps in the process. During freezing and low temperatures, the lack of liquid water causes the production of a higher-quality end product and completely stops most microbe-mediated

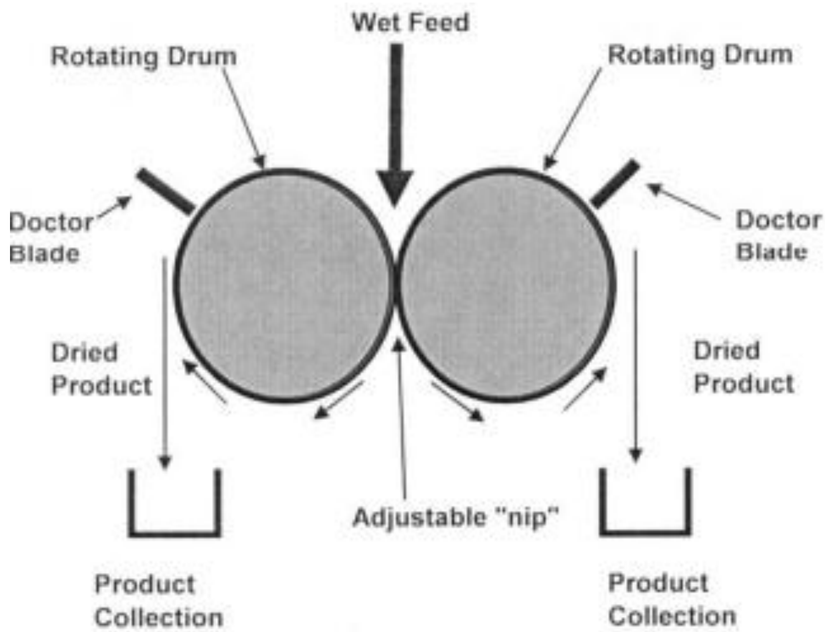


Figure 4. Functional parts of a drum dryer. Source: Adapted from: Mercer (2014).

reactions (Falade and Igbeka, 2007). The food is first frozen (at - 20°C), after which a controlled quantity of heat is supplied under vacuum to induce sublimation, in which ice is converted straight to vapor and subsequently condenses as ice on a refrigeration coil, which is generally kept at -55°C (Claussen et al., 2007; Oetjen and Haseley, 2004). One of the most significant characteristics of freeze dried fruits is their rehydration capacity. The immense expense and quantity of energy used throughout the freezing, drying, and condensing processes are disadvantages of freeze drying products. Because of the long freeze drying period, the product can collapse, resulting in a rough product with minimal rehydration ability and a loss of aroma. Exotic fruits and vegetables, soup ingredients, mushrooms, orange juice, mango pulp, and other industrial applications of the technique have all been effective. Though using a microwavewas able to optimize the freeze drying of onions (Abbasi and Azari, 2009; Schossler et al. (2012) developed an integrated ultrasound freeze drying device to dry bell pepper. The use of ultra sound technology was found to minimize rate of drying by 11.5%.

Vacuum drying

For the drying of fruits and vegetables, vacuum technology is used in conjunction with other drying methods such as freeze drying and microwave. In vacuum drying, pressure-driven flow is the most common mode of moisture migration (Cenkowski et al., 2008; Parikh, 2015). It is carried out below 101 kPa but above 0.6 kPa, with heat transfer normally taking place through conduction. Drying time is shortened since water boils at a low temperature under vacuum due to the pressure. Additionally, the product's water circulation improves, resulting in increased mass transfer. High pressure, on the other hand, can cause product darkening.

Osmo-dehydration

Osmotic dehydration is the process of partially drawing the moisture out of fruits and vegetables by immersing them in a hypertonic solution containing sorbitol, glycerol (sugars of high osmotic pressure) or salt. When food is placed in a hypertonic solution, solutes from the solution diffuse into the tissue of the fruits and vegetables (Mehta et al., 2013). The pretreatment preserves the food color, taste, and nutritional qualities, and it can be done with mild heat treatments. As a result, the energy needs for the overall dehydration process are effectively reduced. Difficulty predicting the final chemical composition of the product and it's taste, unnecessary wastage of osmotic solution, and leaching out of pigment, acids, carbohydrates, minerals, and vitamins are only a few of the issues that must be overcome. According to Kumar and Sagar (2014), fruit drying is more successful when osmotic treatment and vacuum drying are combined.

Heat pump dryer

Hot air drying is inefficient and wastes a lot of energy. As

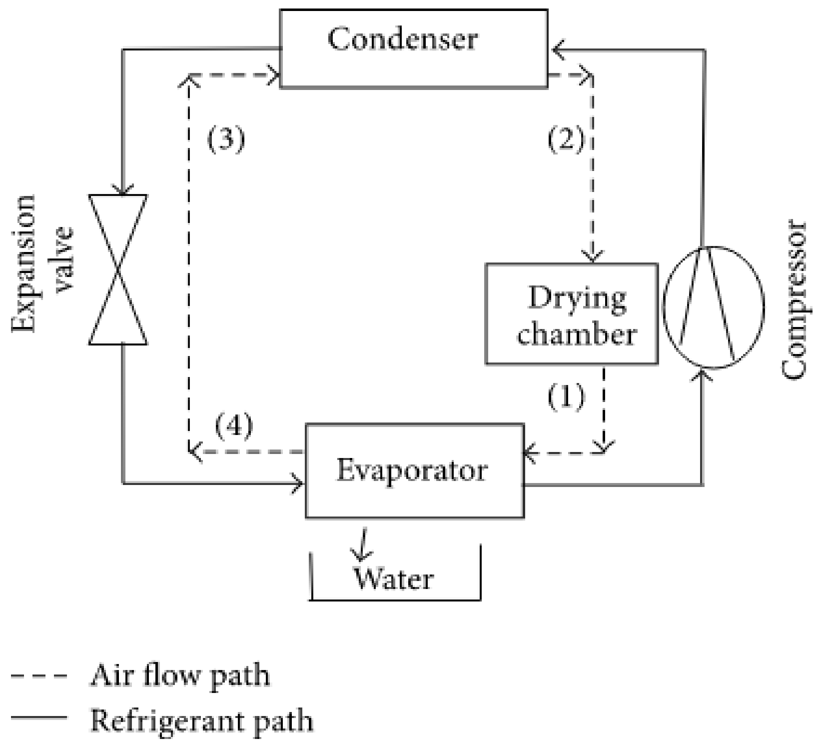


Figure 5. Component arrangements of a heat pump dryer.
Source: Fayose and Huan (2016).

a result, numerous approaches focusing on recovering exhaust air during the manufacturing process have been developed. The heat pump drier was created with this objective in mind (Calín-Sánchez et al., 2013). In this type of dryer, a refrigerator is employed to recover latent heat by water condensation (Figure 5). Dry heated air is provided to the product as a result of the process, resulting in the release of humid air. In the heat pump evaporator, the air is condensed, allowing the latent heat of vaporization to be utilized for warming the drying air. Heat pump dryers improve energy efficiency while reducing fossil fuel consumption (Fayose and Huan, 2016). The advantage of this drying procedure over a standard hot air dryer is the reduction of time and temperature due to the lower relative humidity (Moses et al., 2014; Rahman, 2020). Heat pump drying also takes less time to dry than other drying technologies and is easy to design, making it ideal for low-tech countries in the Sub-Saharan region (Fayose and Huan, 2016). Heat pump drying technology has been combined with other drying processes to overcome some of its flaws and generate improved product quality, cheaper energy consumption, and increased thermal efficiency. Heat pump assisted sun drying, microwave drying, infrared drying, fluidized bed drying, air freeze drying, radio frequency drying, and chemical heat pump assisted drying are all examples of heat pump assisted drying. This is especially necessary for heat-sensitive materials like fruits and vegetables, which require only a low temperature (Fayose and Huan, 2016).

Explosion puff drying

The puffing chamber, vacuum chamber, vacuum pump, decompression valve, steam generator, and air compressor are all components of explosion puff drying equipment (Calín-Sánchez et al., 2013). The decompression valve is closed after the food is put in the puffing chamber (Figure 6). Fruits or vegetables sample are heated to 95°C using steam from the steam generator and retained for 5 min while the air compressor raises the pressure inside the equipment to 0.2 mPa. By opening the decompression valve, the pressure is decreased; allowing puff samples to be vacuum dried (Feng et al., 2021). This process incorporates hot air drying and vacuum freeze drying to provide a less expensive alternative to freeze-dried products (Zou et al., 2013; Chen et al., 2017). Inadequate knowledge of the hygroscopic properties of fruit or vegetable to be dried leads to poor product. Furthermore, nutrient losses due to high temperatures during vacuum drying are a significant disadvantage of the method (Feng et al., 2021). Puff drying works well with diced carrots, resulting in a product that browns minimally and rehydrates well when put in water (Kerr, 2013).

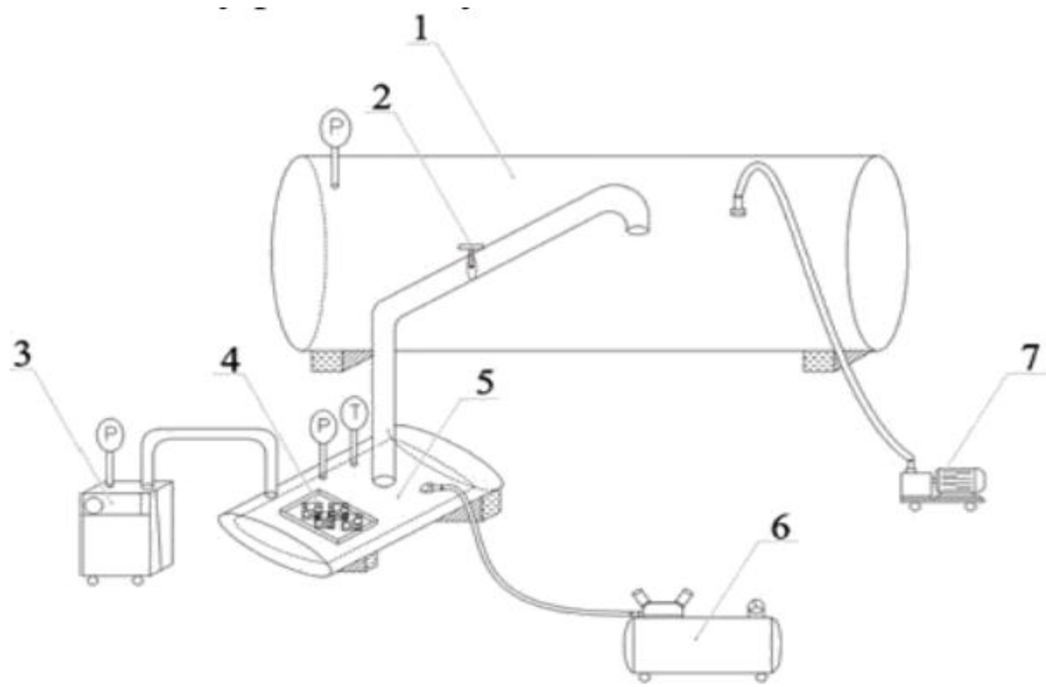


Figure 6. Schematic diagram of explosion puff drying device and accessories. Source: Fan et al. (2018). 1 = Vacuum chamber, 2 = Decompression valve, 3 = Steam generator, 4 = Food samples, 5 = Puffing chamber. 6 = Air compressor, 7 = Vacuum pump.

Low-pressure superheated steam drying

The dehydration process takes place in a sealed drying chamber with a low pressure maintained by a vacuum pump. To prevent excess steam condensation, a steam trap is installed in the reservoir that receives the drying agent from the boiler. The use of a heater with a temperature control device considerably reduces the first steam condensation during the start-up cycle. Calín-Sánchez et al. (2020) suggested the use of a variable-speed electric fan to distribute steam in the drying chamber (Figure 7). According to Sehrawat et al. (2016), the process results in better retention of bioactive components with reduced oxidative changes. However, during drying, the steam collects dust, particles and solids from the raw material. This process has been used to successfully dry onions (Sehrawat and Nema, 2018).

Electromagnetic radiation techniques

Many traditional drying methods rely on hot air provided by an electric heater or gas to assure heat transmission, typically by convection, between the hot air and the food. The electromagnetic wavelength spectrum, on the other hand, is used as a source of energy in several other approaches. A precise wavelength of electromagnetic waves reaches out to the product, producing heat and speeds up the drying process (Rahman, 2020). The method works by indirect electro heating because electrical energy is first converted to electromagnetic radiation before being translated into heat in the food product (Marra et al., 2009). Some of the drying procedures that make use of this principle are as follows:

Refractance window technology: Refractance window drying is a new method of drying that uses circulating water at atmospheric pressure to deliver heat energy to dehydrated food (Pragati and Preeti, 2014; Niakousari, 2018; Kigozi et al., 2021). Any heat that is not used is recycled, and liquid forms of fruits or vegetables to be dried are spread out on a clear plastic conveyer belt. Food on the moving belt dries in a couple of minutes, as opposed to hot air tray or tunnel dryers, which take several hours, or freeze dryers, which take even longer. Convection, conduction, and radiation are the three forms of heat transfer pathways used in this drying technique. All of these heat transfer modes worked together to produce an energy-efficient drying process. Food to be treated must be liquid or semi-liquid. The substance is usually an infrared translucent plastic material floating on the heated circulating water area, and it is applied to the surface of a conveyer belt. When infrared energy passes through the water surface, the refractive principle of the water surface provides a window. When moist food and transparent plastic come into touch, an infrared window is formed, allowing infrared energy to be transferred directly to the material (Figure 8). The drying time for this method

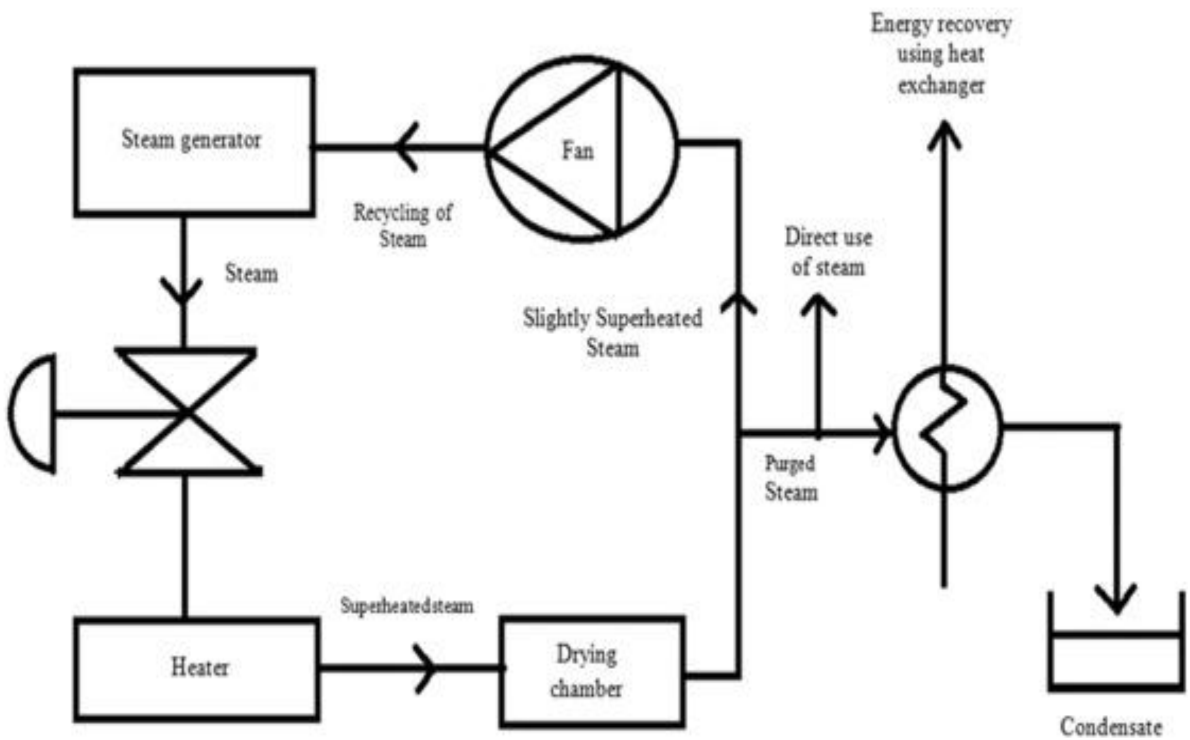


Figure 7. Low-pressure superheated steam drying setup. Source: Adapted from; Sehrawat et al. (2016).

is very limited, according to studies on pure pumpkin (Sabarez, 2016), dehydration through the refractance window takes place at ambient pressure and at lowered temperatures (-30°C), making it a good choice for heat-sensitive foods. According to Nindo and Tang (2007), this method has emerged as a novel cheaper option for dehydrating fruits and vegetables. The sample thickness and drying temperature, however, have an impact on the process. This method can be used to dry berry slices and puree into powder, flake, or sheet form.

Microwave drying: Microwaves are propagated through space using electronic and magnetic fields. Microwave heating is advantageous because it takes less time and heat to reduce the moisture content in foods (Kahyaoglu et al., 2012). The volumetric heating that occurs when electromagnetic waves move through a substance, causing its molecules to oscillate, is the basis for microwave drying. Thermal energy is produced by this oscillation, which is then used to extract water from the wet food. 915 and 2450 MHz are the most used frequencies in the food drying industry. When compared to traditional methods, this drying technology is able to produce high-quality dried products with lower costs and more energy efficiency due to the volumetric heating that is dispersed across the entire food sample. However, according to Joardder et al. (2013), the process causes product harm as a result of insufficient heat control and mass transfer. Microwave dried fruits and vegetables are prone to scorching because of reduced moisture content towards the end of the drying process. As a result, it has been suggested that it should be used in conjunction with other methods, such as the use of microwaves in conjunction with vacuum. Giri and Prasad (2007) used microwave-vacuum drying to prepare button mushrooms As opposed to convective air drying, they discovered that microwave drying takes 70 to 90% less time and retain better rehydrating properties.

Infra-red heating: Infrared drying occurs when a fresh fruit or vegetable is subjected to electromagnetic radiation with a wavelength range of 0.8-1000 µm, which causes infrared drying. Infrared has a wavelength range of 0.75 to 1000 µm (Askari et al., 2013). The heat from the heating source is delivered to the food surface via infrared radiation. The surrounding air, on the other hand, is unaffected by the procedure. This approach is one of the finest for combining with traditional drying processes because of the equipment simplicity and energy savings. Furthermore, rapid and effective heat transfer is recommended, resulting in increased organoleptic and nutritional value of the item, uniform heating, and cheaper final expenses (Boudhrioua et al., 2009). At the atomic and molecular levels, infrared exposure causes charge to accumulate in the electronic state, as well as in the vibrational and rotational states. This causes the food to increase in temperature while the temperature of the air around it remains constant. Agricultural commodities

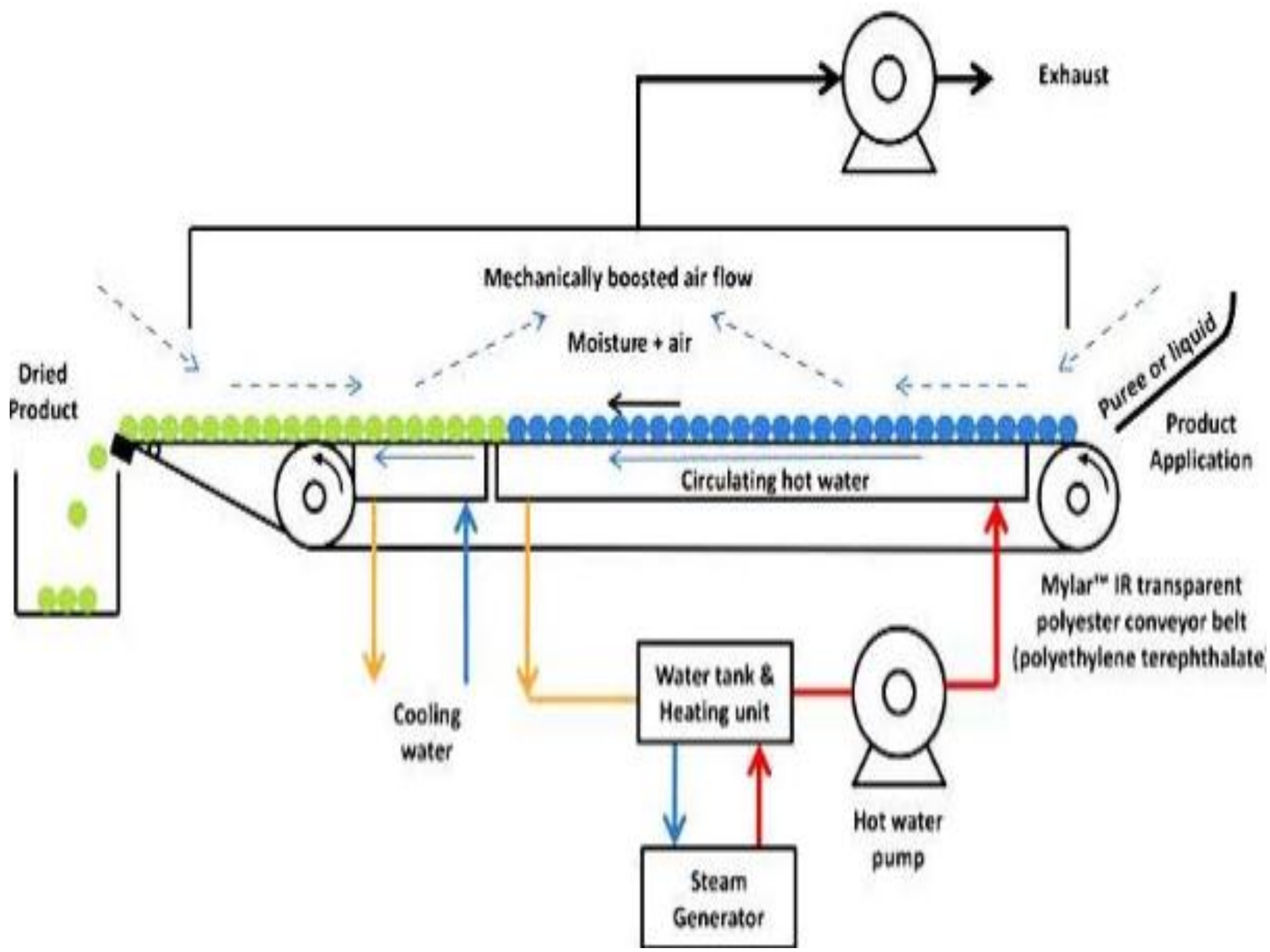


Figure 8. Refractance window drying. Source: Adapted from: Moses et al. (2014).

such as carrots, sweet potatoes, and tomatoes have been dried using infrared drying (Boudhrioua et al., 2009).

Radio frequency drying: This technology can be used not only for wireless communication, but also for food processing. Radio frequency heating is the interaction of an electromagnetic field created by a radio frequency generator with the molecular species in a substance (Caln-Sánchez et al., 2020). As a result, the food sample is sandwiched between two electrodes that are subjected to a 40,000,000 times per second changing electric field. The electric fields, like the polar molecules in the meal, alternate, generating friction and heating the entire product. Because water is bipolar by nature, it heats up and evaporates (Babu et al., 2018). Larger equipment and high operating costs are a considerable disadvantage. Radio frequency has been extensively explored as an alternative to the typical hot air drying procedure in horticulture produce such as apple slices and snack meals (Marra et al., 2009).

Combined drying methods

Combination of drying methods overcome the drawbacks of traditional drying by incorporating the benefits of many methods while reducing the harmful effects that arise when only one technique is used (Chua and Chou, 2014).

Microwave- assisted convective drying

Hot air drying is unsuccessful in drying fruits and vegetables due to the long drying period and use of extremely high temperatures. Microwave-assisted convective drying, according to Calin-Sánchez et al. (2020), can alleviate these issues. As a result, the heated air reduces unbound moisture on the food's surface, while the microwave energy uses volumetric heating to eliminate bound moisture from the product's insides. Nonetheless, according to Kumar and Karim (2017), more research is needed to establish when microwaves should be optimally integrated into the process, such as when the drying rate begins to fall, when the drying rate is already declining, when the drying rate is already falling or when moisture content is reduced.

Convective drying followed by vacuum microwave drying

Calin-Sánchez et al. (2020), describe a two-stage process that begins with convective pre-drying of the fresh food and ends with vacuum microwave drying of the product. Convective pre-drying reduces unbound moisture without altering bioactive components in fruits and vegetables, and vacuum-microwave finishing drying reduces moisture content to the appropriate level. These two combined drying techniques, it has been claimed, are more efficient than either of the methods employed independently. Sour cherries, jujube, orange peel, beetroot, blackcurrant, pumpkin, plums, and hemp, among other fruits and herbs, have proved that the method improves food quality (Calin-Sánchez et al., 2020).

Fluidized bed drying - assisted by microwaves, far infrared rays, and ultrasounds

In a similar way to convective drying, microwave energy can help in fluidized bed drying. This procedure, however, requires numerous drying phases and, in particular, more investigation into its applicability to different products; additionally, the initial device costs are substantial (Calin-Sánchez et al., 2020). It was able to monitor the influence of allicin (the organosulfur component found in garlic) in the drying phase because far infrared rays assisted fluidized bed was employed in the first stage of drying (Calin-Sánchez et al., 2020). When high-powered ultrasound is used on heat-sensitive horticulture commodities, the mass transfer process is accelerated, resulting in a higher-quality dried product. Fruit and vegetable ultrasound procedures have been proven to reduce adverse effects such as shrinking, discoloration, breaking, and nutritional alterations. It is also recognized as a low-cost and energy-efficient system, in addition to having an easy user interface (Singh and Kingsly, 2008).

Intermittent drying of food products assisted by temperature, pressure, humidity, convection, radiation, and microwave

Drying necessitates a significant amount of energy (Calin-Sánchez et al., 2020), discovered intermittent drying as an energy-efficient and successful strategy for enhancing drying kinetics, boosting product quality, and lowering drying process energy consumption. Intermittent drying is when the drying conditions alter over time. Adjusting the drying air temperature, humidity, pressure, and even the heat input mode can help accomplish this (Kumar and Karim, 2017). Intermittent drying was found to be possible by modifying the airflow rate, air temperature, humidity, or operating pressure, all of which can be accomplished by varying the thermal energy source. Intermittent drying can aid to decrease browning impacts and chemical reactions that help to preserve the product's bioactive ingredients in terms of food quality (Pham et al., 2017).

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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