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Drying of vegetable and root crops by solar, infrared, microwave, and radio frequency as energy efficient methods: A review

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ABSTRACT

Fruits, vegetable, and root (FVR) crops are vital to achieve food and nutrition security (FNS), especially in Sub-Saharan Africa (SSA). However, their perishable nature results in losses across the value chain. The review discusses the application of dehydration technologies: solar, infrared (IR), microwave (MW), and radiofrequency (RF) to produce shelf-stable dried agricultural produce. Drying technologies for example IR, MW, and RF use radiation for heat transfer and are more energy efficient compared to traditional hot air drying. Due to shorter processing times and lower thermal load, the nutritional quality and functional properties of dried materials from IR/MW/RF are often superior compared to hot air convection ovens or solar drying. Combination methods with hot air, vacuum and ultrasonication, and pre-treatments are of great interest for higher efficiency and quality. There are, however, limited studies available on the use of IR/MW/RF dehydration technologies for FVR crops in SSA, albeit these technologies have potential and further investigations are required for adoption.

KEYWORDS

Infrared; microwave; radio frequency; ultrasonication; energy efficiency

Introduction

Food and nutrition insecurity is a major challenge that needs to be addressed globally to achieve the United Nations' sustainable development goals (SDG) no. 2 "End hunger, achieve food security and improved nutrition and promote sustainable agriculture" and 3 "Ensure healthy lives and promote well-being for all at all ages" by 2030. Although there has been a decline in food insecurity throughout the world from 2005 to 2014, a reverse is seen from 2014, as food insecurity increased worldwide and about 30% in Africa.[1] Malnutrition is a physical condition caused by a deficiency (undernutrition) or an excess of nutrients. The triple burden of global malnutrition consists of (i) deficiencies of macronutrients (proteins, energy, and "good" lipids, i.e. unsaturated fats) leading to insufficient energy and protein, especially in children, (ii) deficiencies of micronutrients including iron, zinc, iodine, and vitamin A, and (iii) excess of nutrients (especially sugars and trans- and saturated fats) leading to overweight/obesity and their associated diseases. More than 22% (151 million) of children are affected by stunting, while 38 million under five are overweight.[1] Adult obesity and overweight are also on the rise. Food insecurity contributes to underweight/undernutrition, as well as overweight and obesity. These two forms of malnutrition as well as micronutrient deficiencies often coexist.[2] For example, in South Africa, about 25% of children under the age of 3 are stunted; and 44% of children under the age of 5 and 18% of adult women have iron deficiency.[2] In contrast, about 25% of the children and 60% of women are overweight and obese.[2] The higher cost of nutritious foods, in contrast to the readily available cheap energy-dense food, has contributed to this triple burden of malnutrition.

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Root crops, fruits, and vegetables provide nutrient-dense foods to be considered to achieve food security and nutrition. Most fruits and vegetables are good sources of vitamins, minerals, and dietary fibre compared to refined cereal flours used as a staple in many African countries. Nunnery et al.[3] showed a negative correlation between food security among low-income pregnant women and the availability of fruits and vegetables.

Fruits and vegetables are also good sources of bioactive compounds, for example, phenolics and carotenoids (including provitamin A ones), with health benefits. Root crops, e.g. cassava and sweet potato, are important as food security crops. Flours from orange-fleshed sweet potato (OFSP) can be a very good candidate for complementary food as it is lower in viscosity compared to cereal flours.[4] This property allows infants to have a nutrient-dense porridge that is bio-fortified with provitamin A when used in combination with a good protein source. Fruits and vegetables can also be used as ingredients for food-to-food fortification.[5] Examples of this are green banana flour and moringa powder which are rich in nutrients and can be used as functional food ingredients.[6,7] Food-to-food fortification is most often affordable and provides a more holistic approach compared to the addition of micronutrient mixes.

In Africa, the production of apples, mango, cassava, sweet potato, banana, plantains, carrot, and turnips has been between 63.22 and 117.66 indexes,[8] corresponding to a value of 4 to 6 billion USD per year (Fig. 1). In addition, there are several indigenous fruits and vegetables available but with limited cultivation in Africa. These indigenous fruits and vegetables are less known and are generally climate-smart crops. Examples of indigenous climate smart fruit are Marula, Kei apple, Balanite, Imbe and wild Medlar.[9] Fig. 1, also shows that root crops such as cassava and sweet potato are important due to high production.

Root crops, fruits, and vegetables have limited shelf-life that contributes to post-harvest losses due to transpiration and microbial spoilage. In addition, postharvest losses can also be due to defective and low-quality products that are not marketable. It is estimated that over 13.8% of food is lost from postharvest to distribution worldwide.[1] Among the postharvest losses, fruits and vegetables account for about 22%; and root and tuber crops for more than 25%.[1] In SSA agriculture, the losses are highest in distribution and sales (Fig. 2).

It is important to note that in terms of SDG 12: 'Ensure sustainable consumption and production patterns, the target 12.3 calls for 'the halving by 2030 of per capita global food waste at the retail and consumer levels and the reduction of food losses along production and supply chains, including post-harvest losses.' The reduction of on-farm losses is likely to have strong positive socio-economic impacts, especially on small farms in low-income countries with a high prevalence of food insecurity.

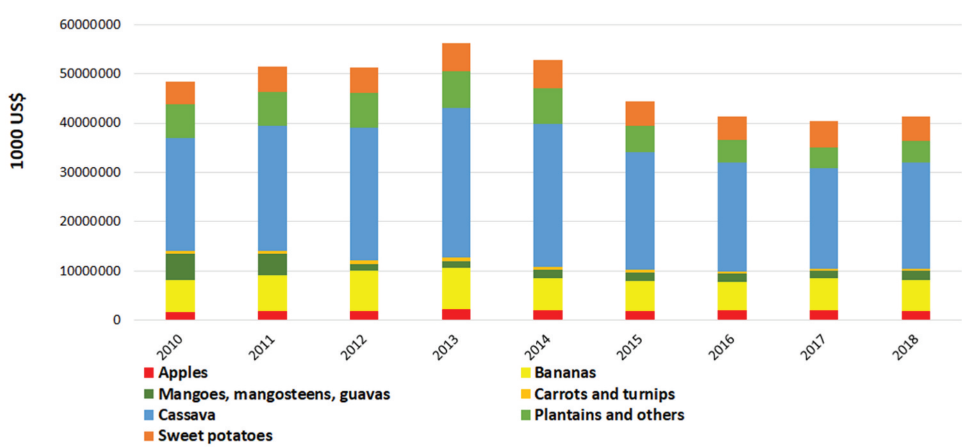

Figure 1. Gross production value of selected fruit, vegetables, and root crops[8].

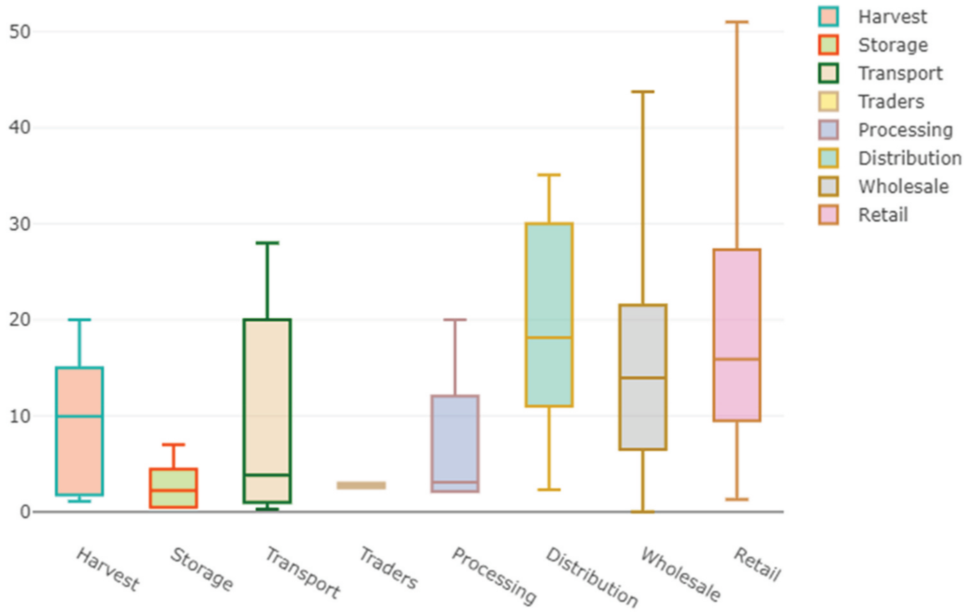

Figure 2. Fruits and vegetables losses throughout the value chain in Sub-Saharan Africa from 2010 – 2017[8].

There are various strategies to reduce postharvest losses for economic benefit. Low-cost options are better suited in an African environment where resources are limited. At the farm level, adequate harvesting time, simple pre-treatment, cold chain, and appropriate packaging are well known to extend the shelf life of fresh fruits, vegetables, and root crops. Additional extension of shelf life requires processing; for example, dehydration or canning. Fruits, vegetables, and root crops that can be rehydrated or milled into flour are attractive alternatives for long-term storage. The flour can also be used as porridge or as raw materials in further processing, for example, extrusion to produce ready-to-eat snacks.

Drying is one of the oldest food preservation techniques. It removes the water from food products, thus drastically reducing water activity, and generally can produce food materials close to or below the glass transition temperature.[10] Solar drying technologies are commonly used in a rural environment in Sub-Saharan Africa (SSA) by small-scale farmers. In contrast, mostly convection ovens are used at the commercial level. Energy usage during drying, time, and quality of the dehydrated products are important factors to be considered.[11,12] Energy-intensive technologies can have a higher carbon footprint, and this is not advisable to achieve SDG 17, climate action. Thus, novel technologies with a low carbon footprint for example infrared (IR), microwave (MW), and radiofrequency (RF) are new opportunities for food dehydration.

The objective of the present review is to discuss recent developments in combination drying technologies that can reduce the drying time and/or energy requirement of the drying process. More specifically, IR, MW, and RF assisted drying, combined with pre-treatment processes as novel drying strategies for fruits vegetables, and root crops will be compared to conventional ones in terms of energy usage, nutritional and functional quality. The raw materials discussed are all from SSA, specifically: mango, banana, and apple as fruits; spinach, amaranth, and moringa as green leafy vegetables; green bananas, sweet potatoes, cassava, and carrot as root crops.

Solar drying and drying mechanism

Solar drying is one of the ancient renewable energy source technologies that use solar radiation to dry food products. A typical solar dryer is composed of a drying chamber, air heater, and airflow system and is classified according to air movement, mode of heat transfer, and type of drying chamber.[13] Based on these classifications, solar dryers are grouped into two main groups; passive dryers which work on natural air circulation, and active dryers which operate on forced air circulation, and both can operate in a combination of passive and active drying termed mixed-mode drying (Fig. 3).[14,15] Passive dryers transfer heat directly, while active dryers rely on a solar radiation collector to heat the surrounding air which is then transferred to the drying chamber in an indirect drying mechanism.[16] In mixed mode dryers, a collector preheats the air before entering the drying chamber and the solar radiation additionally heats the products placed in the drying chamber.[13]

Solar drying in developing countries presents energy, operational, and economically cost-effective methods to dry food.[17] The development of hybrid and/or forced convection solar dryers to improve the drying process has gained popularity.[18] The natural convection dryers are modified to either include a fan, auxiliary heat pumps, integration of a solar photovoltaic system, and sun-tracking devices.[17] These modifications provide accelerated airflow thus increasing the drying rate.

For example, the solar tunnel dryer consists of a drying chamber with a tunnel-style square shape and a blower to remove heat in the product. Solar panels used with this dryer can either be monocrystalline, polycrystalline, or thin amorphous films of which a 12 V, 17AH rechargeable battery is used to store the panels' electrical power. A blower transfers the air heated by the panels through the tunnel. Thus, the blower controls the air flow rate.[15] A greenhouse version of this dryer has also been developed where a drying tunnel of transparent plastic wall houses lines of trays with the product. The air from the greenhouse is distributed to the tunnel by an electrical fan while the transparent walls function to transfer solar radiation to the product. This dryer provides continuous production, labour costs are reduced, and lower energy consumption.[18]

A liquid petroleum gas (LPG) burner can also be used as an auxiliary heat source to assist in the movement of air inside the radiation collector to the drying chamber in forced convection dryers. Recycling of the heated air is possible with the LPG-operated dryer since the air is circulated in the chamber to save energy. On the other hand, PV-operated solar dryers can be used without electricity as an indirect, solar tunnel with a plastic cover or polycarbonate, greenhouse, or roof-integrated solar dryer.[18] These are ideal in communities without electricity supply. As with natural convection dryers, process optimization is critical to maintaining product quality. Temperature is monitored using thermocouples in electrically ventilated solar drying systems.[17]

Irrespective of the drying mechanism, food drying is based on two factors: heat transfer from the surrounding environment to the product surface and mass transfer from the intracellular parts of the

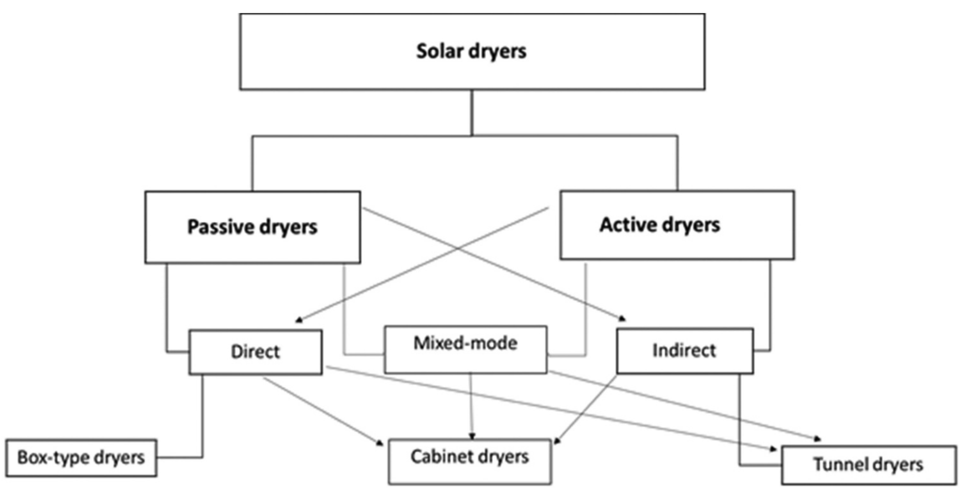

Figure 3. Solar dryer types (adapted from Leon et al.[14]).

product to its surface.[19] The heat and mass transfer are influenced by product characteristics, process parameters, and environmental parameters (Table 1).[14] In addition to the stated product parameters in Table 1, chemical changes during drying, degree of maturation of food material and thermal conductivity are also important.

The major benefit of solar drying is the low cost compared to fossil fuel or electricity-powered drying technologies albeit it can only be done during daylight. Concerning food quality, solar drying is reported to dry foods successfully without altering the colour, taste, and appearance of food; it reduces the risk of microorganisms and prevents insect infestation and contamination by foreign matter and toxins.[13] However, these are dependent on the solar dryer design, prevailing drying conditions, and the composition of the food product. The nutritional quality of fresh produce is mainly determined by the contents of ascorbic acid (AA) and β-carotene, two antioxidative micronutrients/vitamins, with a high sensibility to light, oxygen, pH, heat, and the occurrence of oxidative enzymes and metallic catalyzers.[20,21] Under most drying conditions, these vitamins have low stability and their degradation is evident, thus they are regarded as nutrient quality indicators during processing. The degradation of these vitamins follows first-order kinetics accompanied by the development of by-products with lower biological activity.[20] The degradation of macronutrients on the other hand mainly affects functional properties and is based on the changes in molecular size due to physical, chemical, and physicochemical modifications during processing.[22] Furthermore, the colour of fresh produce is affected by the drying temperature, exposure time at this temperature, and sugar concentration.

During thermal processing, all-trans-β-carotene is isomerized to 13-cis isomers whereas exposure to light results in the formation of 9-cis isomers because of exposure time and physiological state of the carotenes.[23] During solar drying of mango, cis-isomers were reported to be between 36.8% and 64.2% and this was supported by the decrease in all-trans-β-carotene. The 13-cis-isomers were the most abundant while the 9-cis-isomers were found as traces. The isomerization of β-carotene was indeed linked to thermal energy as the mangoes were dried between 7 and 8 h at an air-drying temperature of 75°C.[23] The increase in total carotenoids resulted in a 25% increase in antioxidant activity (Table 2) which is attributed to the morphological changes which allowed for the extraction of carotenoids and phytochemicals.[22,26]

The aerobic degradation of ascorbic acid during food processing is through oxidation into dehydroascorbic acid. Ascorbic acid (AA) retention is dependent on air (oxygen) and surface exposure, which is the most critical factor,[20] temperature, time, food composition/structure, and pre-treatments. Increasing the surface area enhances degradation. Although the drying chamber in indirect solar drying is conducive to retaining high temperature for longer, the product is not directly exposed to the sun as compared to open sun drying and an extent direct solar drying. In this case, the product mainly experiences surface casing as direct exposure to UV rays.[20] Pre-treatments such as chopping and cutting have a role in increasing the surface area of the product and thus can lead to accelerated degradation due to the heat and the exposure of the intracellular cells to oxygen. Sliced banana and mango exhibited a greater than 75% decrease in AA (Table 2) irrespective of the surface area. This degradation is attributed to the high drying temperature (60°C) and long exposure (>6 h) at this temperature. However, the use of a pre-treatment such as blanching enables retention of vitamin C due to the inactivation of the ascorbic oxidase as observed in apples (10.21 mg/100 g AA for

Table 1. Factors affecting drying process[14,109].

Product parameters (variable)	Process parameters	Environmental parameters
Physical properties – size, density	Thermal performance – drying time/drying rate, airflow rate and temperature	Temperature of air
Moisture content	Type, size and shape dryer	Relative humidity
Mass-heat transfer coefficient air and food	Drying capacity and efficiency	Flow rate of drying air

Table 2. Effect of solar drying conditions on nutrient composition of fruits.

Commodity	Solar drying	Moisture content (%, dwb) Initial	Final	t (h) T (°C)	Findings: Nutritional and Functional aspects	References
Apples	Indirect	61.6	7.99	6-10 40-60	25% decrease in AA	[24,25]
Banana	Indirect	75.57	NA	6 60	74% decrease AA, 23% increase antioxidant activity	[26]
Plantain banana	Direct	63-79	10.18	48 50	2.7% decrease in L* water and oil absorption capacity affected	[27,28]
Mango	Direct	79.63	NA	6 – 8 50[2]-60	78% decrease in AA	[23,26]
Carrot	Direct	90.5[3]	8.2[3]	10- 14 27-50	49–68% loss in β-carotene	[29]
Cassava	Direct	80-	4	5 68	Decrease in carbohydrates, AA	[30,31]
	Indirect	74.5	20.3	6 71[4]		[30,32]
OFSP	Direct – tunnel dryer	NA	9.9-10	5.7 28.3 - 63	7–21% total carotenoids loss and 9% decrease in all-*trans*-β-carotene	[33–35]
Spinach	Direct – tunnel dryer	88.2–94.0[5]	3.50–5.13	6.3-10 NA	NA	[36,37]
Amaranth	Direct	NA	NA	4–6; 45-55	Isomerization of all-trans-β-carotene and all-trans-α carotene to 9-cis-β-carotene	[38]

NA-not available.
AA- ascorbic acid.
[2]Fruit temperature for 5.5 h.
[3]As is basis.
[4]Maximum temperature reached in the drying chamber.
[5]Wet basis.

blanched followed by convective solar drying) versus 7.66 mg/100 g AA for a solar drying treatment only.[24]

The colour of an apple and plantain banana exhibited heat-related changes as observed by a browning index of 0.21 Abs/0.1 mg and a 2.73% decrease in lightness (L*) respectively.[24,27] Both fruits were dried at temperatures between 40°C and 60°C which contributed to browning due to the Maillard reactions. Both fruits contain sugar, with the plantain banana dried at the yellow-ripe stage (stage 5) of maturity and total soluble solids of about 20° Brix.[27] During the final stages of drying the water has evaporated from the surface layer of the product. This causes case hardening and less evaporative cooling from the surface which might lead to unintended browning.[39]

Sagar and Kumar[39] argued that structural shrinkage and collapse are caused by glass transition (Tg) since there is minimal collapse to the product below the Tg. During hot air drying, the temperature of drying is above Tg of the product thus the product goes into a rubbery state and the onset of shrinkage. This structural collapse and shrinkage further affect downstream processing or use of the product and/or its functional properties. The rehydration (water absorption) of dried food products is reported to be rapid at the beginning due to surface and capillary suction. However, this is dependent on porosity, capillaries, cavities near the surface of the product, temperature, air bubbles, amorphous-crystalline state, soluble solids, and dryness. Crystalline structures are reported to be resistant to solvation causing swelling stresses while amorphous regions hydrate faster.[39] Resulting plantain flour from solar drying caused changes in water absorption capacity (WAC) and oil absorption capacity (OAC), where WAC decreased while OAC increased,[27] which was in contrast to the study by Fadimu et al.[28] This is attributed to the morphological changes in flour such as granule rigidity, lipid proportion, amylose leaching, solubility, damage to the crystalline starch structure as well as the maturity of the fruit.[22] Solar dried plantain flour had higher dispersibility and wettability compared to other dried flours and thus would reconstitute faster which is a desirable property in flour.[28]

Infra-red (IR)

IR is electromagnetic radiation often divided into three categories based on its wavelength: the near-infrared (NIR; 0.78–1.4 μm), middle-infrared (MIR; 1.4–3 μm), and far-infrared (FIR; 3–1,000 μm).[40] Since energy from an emitter is made up of several wavelengths, it is important to take into account how the proportion of radiation in each band varies depending on the emitter's temperature and the lamp's emissivity. The amount of radiation impinging on any surface depends not only on its spectral composition but also on its direction.[41] IR drying has received considerable attention lately for drying foodstuffs such as fruits and vegetables. IR radiation can be reflected, absorbed, or transmitted when it strikes a surface. The efficiency of drying can be enhanced when the incident IR is with high absorption and less scattering.[41] During IR drying, heat is transferred to the material to be dried in the form of radiant energy and heating the surrounding air.[42] The delivered energy is applied directly to the sample with no other transfer medium. Water has a very strong absorption of IR radiation at around 2.7–3.3,6.0 and greater than 12.5 μm.[41] The O-H bonds in water absorb the IR energy and start to vibrate with the same frequency as the incident radiation. This rapid internal heating increases the water vapour pressure inside the product which induces the opening of pores thereby accelerating the rate of moisture removal.[43] A stream of cooler ambient air surrounds the sample, and the internal heat drives the moisture out into the cooler air stream which removes it from the process.[44] Infrared radiation can penetrate a material to varying depths depending on the material's thickness, water content, other internal components, and wavelength of the emitting source.[45]

Drying fruits and vegetables have been carried out by IR technology or by combining IR with other technologies as highlighted in Table 3. Limited work has been reported on IR technology for drying vegetables that are commonly found in the SSA region, for example, amaranth and moringa leaves, but the results on fruit and potatoes suggest there is a potential. Nowak and Lewicki[59] reported that a comparison of IR drying with convective drying showed that drying time was reduced by up to 50% when using IR energy. It has also been reported that IR drying alone reduces the sensory quality of fruits and vegetables.[60] It is difficult to compare findings from different studies as researchers are using different units (Table 3) to highlight the output power. Even with the power density, it is difficult to deduce the power output without the angle dimensions.

Hot air, refractance, microwave, vacuum, ultrasonic, and freeze-drying are some of the technologies that have been combined with IR to dry fruits and vegetables. The combination treatment can be pre-, post-, or simultaneous treatments. Guo et al.[53] reported a significant increase in time and energy efficiency during ultrasound (US)-assisted IR drying. This IR drying combination was more efficient since the applied US created more porous structures by acoustic cavitation. The pores promote water migration from the inside of carrot tissue to the outside thereby resulting in a synergistic effect with the IR surface drying.

Most of the work reported does not give data values about energy efficiency, however from Table 3, it is noted that IR coupled or followed by refractance window drying has high energy efficiency (more than 47% saving compared to hot air drying, that is, from 60 min to 20 min drying time).[46] This reduction in drying time was attributed to the synergistic effect of refractance window and FIR heating that leads to rapid diffusion of moisture from the material. The refractance window drying technique involves drying purees and liquids placed over a thin film that allows penetration of infrared and forms a 'window' through which drying occurs.[61] The product temperatures are kept low and rapid drying occurs as all three modes of heat transfer are involved. Selvi[62] also reported that drying time was reduced with increased IR temperature. This could be due to a more rapid mass transfer since more heat was generated within the sample, creating a larger vapor pressure differential between the centre

Table 3. Properties of some dried fruits and vegetables by infrared radiation alone or in combination with other technologies.

Fruit or vegetable	Sample Thickness (mm)	IR (W)	T (∘C)	Combination	Findings	Nutritional findings	Reference
Apple	5	250 × 3 lamps	50 or 60	Refractance window and Hot air	46% saving in energy consumption; product sensory quality retained @ IR temperature 60°C	Increase in total phenolic content from 10.6–14.6%. An increase in total flavonoid content from 20.1–34.5%. An increase in antioxidant activity from 20.2–25%. Retention of ascorbic acid	[46]
Apple	2	556		ultrasound 1,5 kW	increased higher drying rates and energy efficiency was increased from 27.6% to 43%;	Decrease in flavonoid content, total phenolic content and vitamin C. Increase in antioxidant activity	[47]
Mango	5	50-700	60-70	MW & hot air (hybrid)	an increment in the drying rate by 38%; the quality of the samples was not able to retain	NA	[48]
Mango	13	266	60	hot-air at 60°C	Pre-treatment (citric acid+ ascorbic acid+$CaCl_2$+ NaCl) improved colour attributes and preserved the microstructure	Retention of ascorbic acid. An increase in total phenolic content	[49]
Banana	5	3000–5000 W/m^2	62.8.	sequential infrared radiation and freeze-drying	72.3%-time reduction or improvement of processing efficiency for a 20% weight reduction; additional acid dipping improved product colour and reduced required drying time	NA	[50]
Banana	3		70-90	Low pressure super heated steam	high temperatures Increased crispness & darkened the colour of product	NA	[51]
Carrot	6	300-500		None	drying rate increased with increasing infrared power; 500W reduced drying time by 44%	NA	[52]
Carrot	5	900-1500		Ultrasound (0 + 80 W).	drying durations shortened by 21% at 900 W	NA	[53]
Potato & carrot	5	17 KW	80	Hot air	reduced drying time & energy consumption by 48% and 63% respectively	NA	[54]
Sweet Potato	6	1000		None	15% reduction in drying time and no significant effect on the quality of sweet potato	NA	[55]
Sweet Potato	4	1100 W/m^2	50- 70	convective drying	more homogenous distribution of product temperature and reduced drying time	NA	[56]
Sweet Potato	8	104-167		None	increase in infrared power level decreased the drying time by 64%.	NA	[57]
Spinach	5		60°C	None	increased energy efficiency and reduced drying time.	55% decrease in ascorbic acid	[58]

*Blank table cells-There is no information provided by the cited authors, The energy savings mentioned is in comparison to convection drying.
NA- Not available.

and the surface of the product.[63] FIR-assisted refractance window drying can be a potential method to handle heat-sensitive products like apples, to obtain better quality products in a relatively shorter time.[46]

In contrast, IR combined with low-pressure drying has been reported to produce unfavourable sensory properties such as darkening the colour of bananas.[51] The darkening of bananas could be due to both enzymatic and non-enzymatic browning that normally occurs when fruits/vegetables are heated in the presence of oxygen at temperatures that are higher than 50°C.[64] However, since product colour is a surface trait, surface temperature has the most influence on colour change and that could be the reason why IR dried bananas darkened. IR could promote more non-enzymatic reactions than enzymatic ones because of the rapid rise in surface temperatures that favours Maillard reactions but inactivates polyphenol oxidase.[64]

Browning as an undesirable change in the sensory attributes of fruits and vegetables can contribute to post-harvest losses hence the need to find more efficient drying combination technologies that retain the sensory properties. Pan et al.[50] reported that sequential infrared drying, and freeze-drying coupled with additional organic acid dipping improved product colour and reduced the required freeze-drying time of bananas. Combination treatments therefore not only promote more energy efficiency but also improve the functional attributes of fruits and vegetables.[47] With an appropriate choice of IR intermittency as well as osmotic pre-treatment, it is possible to reduce the overall colour change while maintaining high drying rates. During the latter process, colour can also change due to the micro-crystallization of the solute on the surface of the samples.

Pre-treatments were found to be a suitable method for the colour and vitamin C preservation of dried mango fruits. The best colour and vitamin C levels were observed with lemon juice and hot water blanching pre-treated samples.[65] Comparable results (retained phenolic and vitamin C contents, increased energy efficiency, and reduced drying time) have been reported for IR drying with conditions varying from 50-2000W, 50°C- 90°C, and sample thickness between 2–10 mm (Table 3). This suggests that drying with IR has the potential to retain more nutrients compared to convection oven drying.

Although during the drying process, there is an inevitable change in the sensory characteristics and loss of some nutrients in the samples, it is necessary to select an appropriate drying method as in some cases, processing may cause little or no change to the content and activity of naturally occurring nutrients. According to Delfiya et al. 2022[66] the absorption wavelength regions of major food components such as proteins, lipids and sugar overlap with the water absorption region. Since the absorption of IR light by water within a food material is dominating over all wavelengths, it is difficult to remove water without impacting other food components in practical applications. A few researchers have reported on the effect of infrared drying on the nutritional properties of food samples. A study by Rajoriya et al. 2020 [46] showed an increase in the total phenolic, flavonoid content and antioxidant activity for 5 mm sliced apples dried using a far infrared assisted refractance window. IR drying might accelerate the breakdown of cellular components and may release more bound bioactive compounds faster. In addition, the rupturing of cell walls might trigger the release of oxidative and hydrolytic enzymes, which would eliminate the antioxidant chemicals in the final product. IR temperature would deactivate these enzymes and prevent the loss of some bioactive compounds.[67] The drying of ginger using catalytic infrared energy was studied by Boudhrioua et al. 2009.[67] They observed a retention rate of phenolic acid and flavonoids after drying with catalytic infrared drying compared to other drying methods. They found that the catalytic infrared radiation inactivates oxidases during drying, thereby reducing the loss of phenolic compounds. Drying functions to inactivate the enzymes polyphenol oxidases.[68]

Most available research does not compare the type of IR (near, mid and far) used, although Xu et al,[69] Xi et al,[70] and Onwude et al.[55] reported that FIR resulted in a significant reduction in drying time and energy consumption when drying carrots and potatoes. Hence there is a need for more research on the type of infrared used and the impact on the nutritional properties and the drying time/energy consumption.

While working with blueberry leaves, Borda-Yepes et al.[71] reported that MW technology resulted in better drying than IR. This presents an opportunity for extensive utilization of combination treatment when using IR technology in drying fruits and vegetables.

Microwaves (MW)

When using MW on foods, the electromagnetic energy is converted into kinetic energy of the water molecules present because of their dipolarity. As microwaves are heating the water that is to be evaporated and by appropriate design of equipment, it is possible to avoid wasting energy on heating massive drying equipment and large volumes of drying air or other heat and mass transfer media.

The principles of MW combination heating have been comprehensively reviewed by Datta and Rakesh.[72] Uniformity of combination processes must be discussed specifically for each combination, like a combination of MW and conventional oven heating.[73] The different combinations cause different mechanisms of water release e.g., from vegetables.[74]

IR heating or convection heating by hot air or steam is all in commercial use. Due to both the fast volumetric heating by MW and its suitability for combination with other drying methods it is indeed one of the most promising fields for the continued development of new food products.[72] The volumetric heating results in the expansion of water inside the product and the water is forced to the surface. While conventional methods like e.g., hot air drying results in a dry surface (case hardening) and resulting in a drying barrier, this is in most cases avoided by the use of MW. Automated control programs have been the key to making this work in domestic facilities and will also be needed on an industrial scale.

Results from combinations of MW with other technologies for drying the vegetables are summarised in Table 4. The energy efficiency of the equipment is not easily accessible from most of the references. Some are made on a laboratory scale and may not reveal the industrial potential. Also, the wide range of power rates used indicates there are large differences in final product quality limits. The highest drying rate found was 36 W g^{-1} reported for spinach dried with a combination of MW and air at 230°C, resulting in browning of the leaves but not at temperatures of 100 or 180°C.[81]

For most drying methods the geometry of the product, especially the surface-to-volume ratio is important. For microwaves the geometry of the product to be dried influences the electromagnetic field as observed by Arikan et al.[88] When drying by MW the temperature of the vegetable is dependent on the saturation pressure of water, i.e., 100°C, at atmospheric pressure if all the MW energy is used for evaporation. Only when there is not enough residual water to evaporate by the supplied power the temperature in the vegetable may exceed the boiling point. However, when most of the water is evaporated the absorbed power is reduced as well in MW ovens with an efficient controller. By use of vacuum, the saturation temperature is reduced, which makes it easy to limit the maximum temperature and is, therefore, a method to consider for heat-sensitive vegetables. The use of vacuum did not reduce the drying time when comparing the same conditions with MW only but created a more porous texture and loss of beta-carotene in sweet potato and carrot.[77,89] Several studies have shown better retention of beta-carotene for MW drying than for convection air techniques.[95] Bettega et al.[89] demonstrated a higher loss of beta-carotenes for MW under vacuum compared to MW only, which is contradicting the results reported by Cui et al.[90] The different findings could be explained by the blanching operation (70°C for 3 min before the drying) used by Bettega et al.[89] Cui et al.[90] found that blanching is not required for the retention of beta-carotenes when using the rapid oxygen-free MW vacuum drying to preserve the colour. It was further shown by Bettega et al.[89] that drying time was not

Table 4. Properties of some dried fruits and vegetables by microwave drying alone or in combination with other technologies.

Sample Dimensions (mm)	MW (W)	Drying (Comparison)	T (∘C)	Findings	Nutritional findings	Reference
OFSP and Purple Fleshed Sweet Potato (PFSP)	3.6 KW/m^3 and 2.5 min of drying time	Pre-treatments; blanching, osmotic dehydration and ultrasound. Combination; vacuum	65	Decreased degree of crystallinity	Good retention of phenolics, carotenoids, and anthocyanins.	[74]
PFSP	2.5 W g^{-1}	Pre-treatments; blanching by mw, steam (98°C) or water (98°C).	80	Blanching pretreatment inhibits browning and reduces processing time.	A serious drop in anthocyanin level occur during microwave-assisted spouted bed drying (MWSB). Blanching pretreatment increases anthocyanin retention,	[75]
Purple-Fleshed Sweet Potato	NA	Vacuum drying	70	Drying time reduction (6–12 min) compared to hot air drying (600 min)	Improved antioxidant activity and phenolic content	[76]
Sweet Potato	Variable from 10,7 to 2,1 W g^{-1} for 27 min	Vacuum drying	40	High drying rate at low pressure (4 KPa) is possible and improves crispness.	NA	[77]
OFSP	5,47 W g^{-1}	Air drying	NA	MW drying 10,5 min compared to 4 h air drying at 60°C.	Chemical composition, including protein and fiber, was similar in microwave vs air drying	[78]
Yellow Fleshed Sweet Potato (YFSP)	2,5 W g^{-1}	MW spouted bed (MWSB) and vacuum drying	NA	Fast drying rate compared to air drying	β-carotene retention was much better in MWSB drying compared to hot air, but lower than freeze drying	[79]
Spinach	9 w g^{-1}	Air drying	NA	Increasing power gave shorter drying and better quality	NA	[80]
Spinach	Up to 36 W g^{-1}	Hot air convection	Up to 230	High power and temperature caused browning	NA	[81]
Spinach	18 W g^{-1}	Hot air	Up to 70	Time and quality improvement when using MW compared to hot air drying	NA	[82]
Spinach	20 W g^{-1}	Air drying	50-75	Only 0,12 KW h per 50 g energy needed and only 290 s. Difference in color between MWSB and freeze drying is small, color uniformity is superior for MWSB drying.	Good retention of ascorbic acid and colour at 750 W	[83]
Moringa	1 W g^{-1}	Hot air convection	50-70	MW assisted hot air drying (MAHD) five times faster than hot air only. MAHD at 50°C was better than hot air on all quality parameters.	MAHD preserved most of the bioactive molecules when compared to conventional hot air drying	[84]
Mango	1000 W for variable weight 170 to 500 g	Air	NA	Favorable to maintain maximum product temperature in range 95 to 98°C	Total phenolic content was higher in MW dried samples compared to hot air.	[85]

(*Continued*)

Table 4. (Continued).

Sample Dimensions (mm)	MW (W)	Drying (Comparison)	T (∘C)	Findings	Nutritional findings	Reference
Mango	Up to 36 W g^{-1}	Hot air convection	Up to 230	High power and temperature caused browning. Good colour retention at 95 to 98°C. Above 98°C thermal damage began to appear as browning spots	NA	[86]
Carrot Disc (d = 30.5, h = 4)	450 (per 90 g for 50 min)	Convective Hot air, Infra Red, Ultra Sound, Combinations	65	US followed by combined MW/HA showed energy consumption of 31.8 ± 1.1%,	NA	[87]
Carrot Grated (thin and long strips)	900 (continuous + pulses2.23 Wg^{-1})	Convective	20, 65-75	Energy consumption 10.7 MJ/kg when drying to low moisture content by pulsed MW.	MW drying led to 30–70% loss of β-carotene while convective drying only 20% loss.	[88]
Carrot 4	80-160 1-2	5 min (Vacuum, 60kPa)	86 (for vacuum drying) and 100 (for no vacuum)	Drying time savings limited by product quality.	MW drying provided a final product richer in β-carotene	[89]
Carrot (180 g) h = 5 mm	400 (15 min), 200 (30 min), 80 (30 min)	Convective Vacuum, 2.5 kPa (Freeze dry −20°C (24 h), 30°C (3 h))	45-50 55-60	Drying time reductions promote energy saving.	All combinations with MW-vacuum drying preserved total carotene better than hot air drying and similar to freeze drying	[90]
Carrot 10	1 100	Freeze dry	−20/30	Energy consumption reduced by 35–40%	NA	[91]
Carrot	200(	PEF and US	40	Energy reduction of 27 to 49% with PEF/US pre-treatment	PEF/contact US pretreatment improved carotenoid retention	[92]
Carrot	3.5 Wg^{-1}	Vacuum, freeze drying, spouted bed,	50 (for hot air, variable for carrot)	Energy consumption ca. 14 MJ/kg H_2O for all combinations except freeze drying	β-carotene was not significantly reduced during microwave freeze drying (MWFD) but reduced by approximately 25% for the three other combinations. Vitamin C was also better preserved by MWFD compared to the other methods where >40% vitamin C was lost compared to fresh carrot.	[93]
Carrot	1,33 W g^{-1} (46,6 J g^{-1})	combined US +MW	45-47	60% energy reduction compared to air drying. Convective drying with MW assistance with the power of 100 W resulted in the least color changes.	US-assisted convective drying performed better than MW-assisted convective drying in terms of carotenoid and polyphenols retention, but this was not reflected in antioxidant activity.	[94]

The energy savings mentioned is in comparison to convection drying.

dependent on the vacuum, but on the power used. Vacuum resulted in a more porous structure of the carrot slices as also demonstrated for Yellow Fleshed Sweet Potato (YFSP).[79]

Blanching as pre-treatment before drying is effective for the inactivation of enzymes and may inhibit e.g. browning. When using MW-assisted spouted bed drying of PFSP, Liu et al.[75] reported a serious drop in anthocyanin level and browning during microwave-assisted spouted bed drying but showed that MW blanching as pre-treatment caused rapid degradation of enzymatic activity and thus preserved the anthocyanin level.

The potential for energy savings when exchanging hot air drying with MW-assisted drying is good (Table 4). Pre-treatment with US (ultrasound) followed by combined MW/hot air showed the highest drying rate, least specific energy consumption, and shrinkage (23.75 ± 2.22 MJ/kg and $31.8 \pm 1.1\%$, respectively) until equilibrium.[87] To stop the drying process as soon as the desired moisture level is achieved is an effective way to save energy. Spectroscopic methods for moisture determination and dryer control have been developed for sweet potato and potato.[96]

As the vegetables discussed here are relatively heat tolerant, the sophisticated combination of vacuum and MW drying can be expected to have little potential. Further, combining MW with hot air does not increase the drying rate enough to defend the quality implications and energy costs of using hot air. The MW drying potential is therefore best when combined with room air drying.

Radio frequency (RF)

RF heating is a dielectric heating process that typically involves electromagnetic waves of 1–100 MHz,[97] and the longer wavelength (than MW) results in deeper penetration. In RF heating electromagnetic waves directly couple with food volumetrically, to generate heat. When a dielectric material is subjected to an alternating electrical field, the forced movement of ions and the rotational responses of polarized molecules can cause friction between molecules.[98] This friction generates heat within the product thus avoiding the increasing limitations of the heat transfer rate that originates from a dried surface. In microwave heating, both dipole relaxation and ionic conduction can be dominant heating mechanisms, whereas in RF ionic conduction has the dominant influence on the heating. Hence, charged ions are more important factors influencing heat generation than water molecules in the RF range.[98]

RF heating is characterized by a more uniform electric field than MW, and the resulting volumetric heating can be used to increase the heating rate substantially,[99] and thereby reduce the thermal load in food processing during the blanching of vegetables.[100,101] During RF drying, tissues with higher moisture content may absorb more RF energy and be more heated, compared to tissues with lower moisture. This "moisture leveling" effect can contribute to a more uniform drying during RF heating.[102] But non-uniform heating can also be a challenge that needs to be dealt with.[103]

Although RF drying seems to be a promising technology, there is only a limited number of studies available for SSA fruit, vegetable, and root crops (Table 5). One application that has been studied is the dry blanching of carrots, as free-standing or combined with hot air to achieve a pre-drying step.[100,101] As pointed out by Mao and Wang,[106] RF, when used in a one-step drying process, has several weaknesses. A low heating rate can be seen in the earlier stage and the drying rate can be relatively low.

For drying, RF is most often combined with hot air (RF-HA). Initially, both hot air and RF energy are used to increase the temperature of the product, but when the sample temperature exceeds the air temperature, the air mainly lowers the product temperature and removes the vapor from the cavity.[107] Another potential application is to utilize the technology during the second stage of drying when the dried surface with reduced mass and heat transfer slows down the drying process. Due to the improved heat transfer, RF-heating normally involves a significant reduction of drying time and thermal load,[105] and consequently a reduction in energy demand.

Table 5. Properties of some dried fruits and vegetables by radio frequency drying alone or in combination with other technologies.

Sample Dimensions (mm)	RF [kW] (V/cm)	Drying (Comparison)	T (∘C)	Findings	Nutritional findings	Reference
Banana 8	7,1/kg	Vacuum	50	More uniform drying with vacuum	NA	[104]
Mango 5		RF-Hot air (RF-HA) as second stage drying (Hot air (HA) and Vacuum drying)	60	HA reduced moisture content to 40%, RF-HA- reduced moisture content to 18%. A 38%-time reduction was achieved, as compared to HA	Minor vitamin C degradation, but overall sample quality maintained well, and better than that dried by HA	[105]
Carrot 5 x 5 × 5	[6]	RF-HA: Blanching/ Pre-drying (Hot water blanching/ Osmotic dehydration)	60 ~ 80	Reduced peroxidase level to <5%, moisture content to 60–70%. More energy efficient and generating less wastewater than Hot water blanching/ Osmotic dehydration.	RF-HA blanching gave better retention of Vitamin C	[100]
Carrot 5 x 5 × 5		RF: Blanching (Blanching [95°C, 2 min]) Container geometry)		RF heating uniformity increased with increasing RF electrode gap POD activity was reduced by 90–95%	vitamin C content and redness was better maintained	[101]

NA-not available.
RF- Radio frequency.
HA-hot air.
POD-peroxidase.

Energy demand

All three novel heating technologies benefit mainly from the direct energy transfer to the product, which implies that there is no need to heat processing equipment and hence less loss of energy to the surroundings, except for the required cooling of the RG-generator and MW-magnetron. Comparing the three technologies concerning energy demand, however, poses some challenges. The technologies vary substantially, mainly because of wavelength and hence penetration depth, but also for energy supply, distribution, and uptake. The penetration depth decreases with increasing frequency. IR has the highest frequency, and hence the lowest penetration depth. Whereas RF has a high penetration depth, and the penetration depth of MW is somewhere in between. This implies that both the surface area and the sample geometry (thickness) are of key importance, as well as the changes that take place during drying. Gou et al.[108] attempted to compare the three technologies by supplying an equal amount of energy (20W/g), to similar sample strips (6 x 1 × 1 cm) of purple-fleshed potato. Although the main focus was on nutritional aspects, the drying curves and temperature development demonstrate the main effects.

From Fig. 4a, it can be observed that the most rapid drying, by far is achieved by MW. This is not surprising when observing also the temperature development in the sample, shown in Fig. 4b. It is clear that the sample geometry (thickness), as well as material (dielectric) properties, are well suited for the MW, and the energy uptake is very high. For IR, the energy uptake is restricted by the surface area to the volume ratio and the heating is very slow compared to electromagnetic heating.

For all drying technologies, an airflow is required to remove evaporated water and maintain a non-saturated atmosphere for the products to be dried. For IR heating, this may cause a heat loss, while this loss is limited for electromagnetic heating.

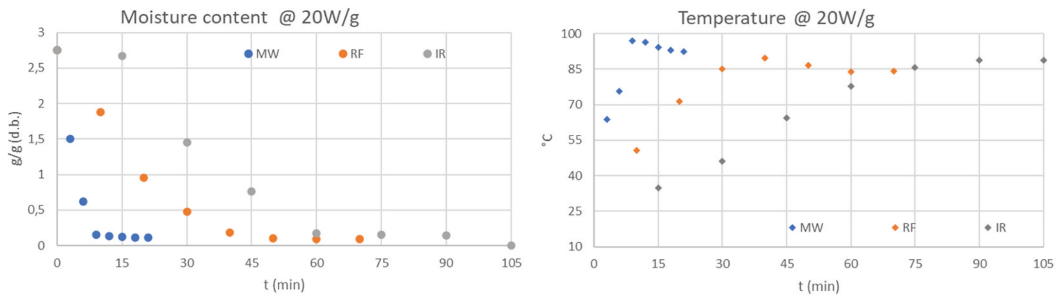

Figure 4. 108], with permission.

Concluding remarks

Fresh produce is highly perishable due to the inherent high moisture content (≤80%) which affects shelf life. This has led to a high amount of waste due to postharvest losses. Drying as a technology to produce a shelf-stable product is relevant in SSA. The choice of drying technologies is important as it must be affordable in terms of capital investment, running, and maintenance costs. The technology should also apply to small and medium enterprises. Moreover, adaptable technologies at the household/subsistence farm level are also of importance. The choice of technology is also determined by the end use of the product, desired characteristics, and available infrastructure to preserve the product. Solar drying is a preferable technology used for the shelf-life extension of fresh produce when the use of energy-consuming technologies is not feasible or accessible. However, the nutritional and food quality after solar drying is less than for other drying technologies. This is related to drying time and temperature were heat sensitive and enzymatic/oxidative degradation of vitamins and other nutrients can occur. The mechanisms of dehydration in terms of moisture loss resulted in lower quality products especially those related to rehydration. Thus, research on solar dehydration should target the pre-treatment of raw materials to avoid lower-quality products. Although, solar drying is a cost-effective technology; dependence on weather is a major limiting factor in the use of this technology. Thus, the use of solar panels and concentrators that can store energy for use during the night is an important consideration.

The drying mechanism for solar and convection ovens is different from that of IR, MW, and RF. The latter three use radiation as the common heat transfer and are advantageous as it generally takes less time and energy to dry fruits, vegetables, and root crops. The reduced drying time is important as it can contribute to preserving the nutritional quality. The mode of heat transfer for water evaporation (mass transfer) for IR, MW, and RF results in the limited formation of hard case phenomena to produce products with good functional properties.

The novel drying technologies enable significant energy savings compared to traditional hot air drying. Comparing the novel drying technologies, it seems that MW and RF are more energy efficient than IR. However, the quantitative comparison is not possible within and between the technologies. This is because (i) some literature does not report the energy (ii) the units are not the same (iii) the oven types and methodologies are different (iv) combination treatments. Moreover, several studies do not report the types (near, mid or far) of IR used for drying. Thus, specific research comparing energy usage and its impact on the quality of various dried fruits, vegetables, and root crops is important for future research.

Combination treatments for example MW with a convection oven and pre-treatment can also improve the drying efficiency in terms of energy as well as quality, both nutritional and functional. The most combination has been with convection (hot air) ovens and some research has included ultrasound, and/or vacuum ovens. Combination with ultrasound increases the drying rate changing the microstructure so that the water can diffuse faster within the food materials. Hot air and vacuum improve water removal as they create a differential vapour pressure for improved water diffusion (mass transfer) from the materials. The latter strategies can also be included in modern solar dehydration design. Pre-treatment for example blanching, acid dip, and salt addition are also important considerations when using dehydration technologies.

There is limited literature on novel drying technologies, especially RF. Moreover, data on the drying of indigenous crops for example amaranth, cassava, and plantain banana are limited. Most research and application of the novel technologies have used sliced fruits, vegetables, and root crops. It is also imperative to consider the dehydration of whole fruits, for example, marula and wild medlar, by the novel processing technologies. The novel technologies discussed in this paper can promote the production of high-quality shelf-stable dried fruit, vegetables, and root crops. This will enable whole year-round access to the dried fruits for food and nutrition security. The dried fruits, vegetables, and fruit as flours can also be used as ingredients in various food products and even food for food fortification for micronutrients and dietary fibre.

It is also notable that poor infrastructure and relatively expensive and unreliable energy (a reliable electricity provider) must be considered in the choice of technologies. The energy efficiency and shorter drying time of IR, MW, and RF compared to hot air/convection ovens will reduce the running cost of production and the latter is a very decisive factor for small and medium enterprises. Energy-efficient technologies will also enable SSA to achieve the two SDGs: 12- sustainable consumption and production patterns and 13: Climate action.

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