Solar fruit drying technologies for smallholder farmers in Uganda, A review of design constraints and solutions

N. Kiggundu[1], J. Wanyama[1*], C. Galyaki[1], N. Banadda[1], J. H. Muyonga[1], A. Zziwa[1], I. Kabenge[1]

(1.Department of Agricultural and Bio-Systems Engineering, College of Agricultural and Environmental Sciences, Makerere University, P.O. 7062, Kampala, Uganda

2. Department of Food Science and Technology, College of Agricultural and Environmental Sciences, Makerere University, P.O. 7062, Kampala, Uganda)

Abstract: Solar fruit drying is a technology that is successfully applied on both domestic and commercial scale among smallholder farmers in Uganda. However, existing solar drying technologies are marred with multiple deficiencies such as inefficient conversion of trapped solar radiation to meet required enthalpy, low throughput, long drying times, and inherent difficulty to achieve acceptable hygiene among others. This review critically examines existing solar drying technologies in Uganda, highlighting design constraints and plausible solutions for supporting the growing fruit drying industry. The common types of solar dryers in Uganda are the static-bed box type solar dryer model, the PPI tunnel solar dryer model, the NRI Kawanda cabinet solar dryer, the hybrid tunnel solar dryer and the UNIDO solar hybrid dryer model. Findings reveal that the challenges characterizing existing dryers in perspective of design are attributed to; poor material selection, poor mass and energy transfers, total dependence on solar energy, lack of capacity by local craftsmen to replicate new and improved models, difficulty to clean the dryers caused by inapt model configurations, and high cost of installation to mention a few. Therefore, a need exists to develop efficient and affordable designs using scientifically proven methods such as Computer Fluid Dynamics to pre-test and optimize the dryer and incorporating alternative energy sources in the design to ensure an all-weather dryer. Additionally, disseminate such innovations to farmers, retool local artisans with quality fabrication skill sets, and develop simple manual with standards and fabrication procedures for the fruit dryers.

Keywords: solar fruit dryers, smallholder farmers, design considerations, design standards

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1 Introduction

Uganda is located in the Sub-Saharan part of Africa where over 50% of the population is affected by deficiency in vitamins and minerals (Tulchinsky and Varavikova, 2009). This is despite of the region being home to hundreds of fruits which can supply the required vitamins and minerals at relatively very low cost. This scenario has been greatly attributed to seasonal inclusion of most of the fruits to the staple diets due to; seasonality of supply that is limited within only few months of the year, and their gross loss after harvest due to high susceptibility to spoilage (Gustavsson, et al., 2010; Stiling et al., 2012). Up to 44% of fruit is lost after harvest in Uganda, and is due to the limited access to appropriate postharvest techniques. On equal par with the problem of seasonal supply of fruits and related adverse spoilage, which has intensified the food and nutritional insecurity among many Ugandans, there is dire need to explore potential and sustainable ways to prolong the shelf life of fruits and thus extend the period over which they can be accessed. Solar drying is increasingly being recognized as

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***Corresponding author: Joshua Wanyama,** Department of Agricultural and Bio-systems Engineering, Makerere University, Uganda. Email: wanyama2002@caes.mak.ac.ug Tel: +256 779 864036

a suitable way to preserve fruits and this is evidenced in the numerous efforts in improvement and appropriate development of drying technologies (Ekechukwu and Norton, 1999; Pangavhane and Sawhney, 2002; Sharma et al., 2009; Amer et al., 2010; Vijaya Venkata Raman et al., 2012; Prakash and Kumar, 2013; El-Sebaii and Shalaby, 2012; Pirasteh et al., 2014). This is because reduction of moisture content of food between 10% and 20% prevents spoilage caused by bacteria, yeast, mold, and enzymes (Scanlin, 1997; Maia et al., 2012). Drying of fruits and vegetables ensures their continuous supply; reduces postharvest losses, food shortages, and accruing malnutrition (Bolaji and Olalusi, 2008; Diemmodeke and Momoh, 2011; Janjai, 2012; Stiling et al., 2012). Alleviation of fruit loss increases access to phytochemicals, essential vitamins, and minerals like vitamin A, vitamin C, fibre and potassium required for healthier lives. In addition, drying of fruits adds value to the fruit produce through product diversification and prolonged shelf lives (Sharma et al., 1995); improves farmers' income; and reduces postharvest losses; preserves vital micronutrients and enhances mainstreaming of fruits in food value chains and improves the utilization of ecological niches where other staples do not thrive.

Since early 1980s when pineapple and banana farmers through small cooperatives interested themselves in preserving and adding value to their highly perishable produce, they have been depending on simple technologies presented in this document. The basic nature of such systems was a key part of their success – they were affordable, had a short payback period and were easy to construct, operate and maintain. Winding forward two to three decades to today, a good number of these farmers have now grown to the point where these basic solar dryer systems are no longer efficient and are even restricting the volume they are able to produce, and increasingly how much of what they produced can actually be sold. This is because the basic solar dryer systems are generating an increasingly high proportion of rejects on the export market. The rejects are attributed but not limited to: bad and particularly inconsistent weather, poor mass transfers, poor dryer material selection and hygiene issues all contributing to product quality variation among others. These limitations are essentially preventing farmers from moving up a level thus the need to advance the drying technology to match the pace at which farmers have grown their production capacity and to fit in the current global trends in line with food quality and safety demands. Thus, there exists a good impetus to investigate existing dryer designs and models in Uganda with the purpose of retrofitting them to meet the drying needs of fruit farmers in Uganda and the product quality specifications of end markets. This study, therefore, explored the solar fruit drying technologies available to or currently being used by small-scale farmers in Uganda, with a view of understanding design constraints with a view of proposing suitable solutions that will sustain the fruit drying industry keeping abreast of recent developments.

2 Common types of solar fruit dryers in Uganda and their design constraints

To find dryer models that exist in the domain of Ugandan fruit farmers, drying sites where commercial fruit solar drying is conducted were visited. Each site served 10 to 15 farmers who had access to dried fruit exporters for at least 10 years. Commercial drying sites were considered because they have witnessed and had practical experience with various models promoted by different agencies and individual researchers. Assessment was with respect to: materials, drying capacities, heat and mass transfer, supportive energy sources, and changes in product quality.

The static-bed-box type solar dryer model

The static-bed-box (SBB) type solar dryer model is basically a cabinet dryer with no separate air heater in which air circulation in the cabinet occurs by natural convection. These models are widely adopted in Uganda by smallholder farmers in the rural areas. This is justified by their simplicity in design, low construction costs, and no requirement for special-skilled personnel to operate (Misha et al., 2013a). They can be fabricated using simple tools and relatively cheap locally available materials like; wood, papyrus, iron sheets, and a transparent plastic (visqueen). The fruits are placed under the transparent enclosure where solar radiations are entrapped. The solar radiation is directly absorbed by the drying produce and some is absorbed and irradiated by a black painted metal (Toshniwal and Karale, 2013). According to Amedorme et al. (2013), heat gradually gained by drying produce affects moisture removal from the surfaces. The stream of air from the inlet vents carries the vapour away through the outlet vents to the surrounding environment. The major challenge users (farmers and/or food processors) face with the SBB solar dryer shown in Figure 1 is lack of control of the final moisture content of the product, poor solar energy tapping and plastic bag sweating caused by constantly high relative humidity (42.5% ±3.1%) during drying thus prolonging drying times (2 to 3 days per batch), questionable quality rampantly characterized by discoloration and curling of the product, and proneness to intrusion by larger pests, animals and theft. Further, the use of soft woods in tropical conditions gives limited durability of the dryer. Also, the use of paints in the drying chamber poses the risk of heavy metal contamination. Moreover, the SBB has low capacity (30 kg of fresh pineapple pulp per batch of 2 to 3 days). As such, the farmer usually has to install more than 25 dryers to match the production rate, ultimately creating other challenges like; space requirement and cost of managing many units.

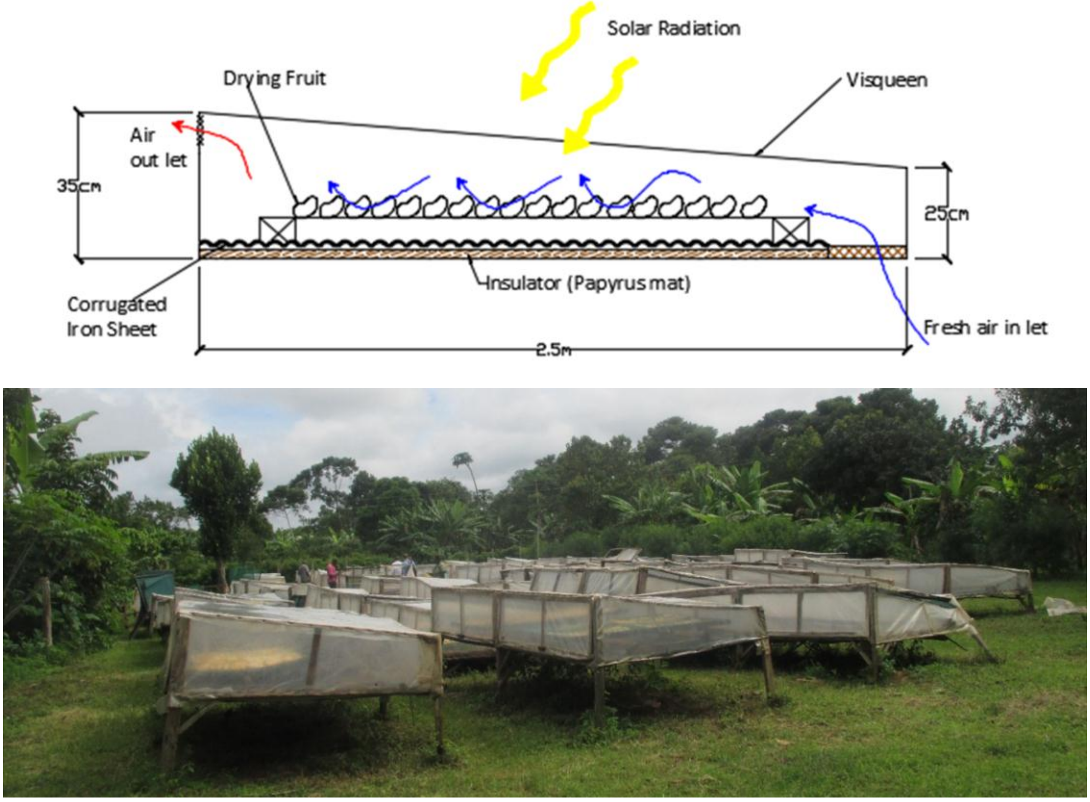

Figure 1 Static-bed-box-type solar dryer model dryer (Credits Galyaki, C)

The PPI tunnel solar dryer model

This model was promoted among farmers by the Patience Pays Initiative (PPI), an organization dealing in crop production, processing and exporting in Kayunga district. The PPI dryer is made mainly out of galvanized steel and is upheld on a brick stand (Figure 2). The dryer is 10.7 m × 1.8 m. This model is durable and can accommodate up to 80 kg of fresh pineapples, or 60 kg of fresh papaya slices. On average, the dryer has an inside air temperature of 47.1^{o}C±4.5^{o}C and relative humidity of

46%±2.5%. The dryer hardly achieves uniform drying due to the long distance the drying air has to move, by the time it reaches the produce laid near the exit, it has become almost saturated thus delayed drying. In addition, there is poor air flow inside the dryer due to; long tunnel distance and dependence on natural convection increases the severity of the problem of delayed drying (≥ 2 days per batch). The model is not widely adopted due to the high cost of installation owing to the hefty cost of galvanized metal sheets. Despite the cost of installation, the maintenance costs are low since only the plastic is replaced every 2 to 3 years.

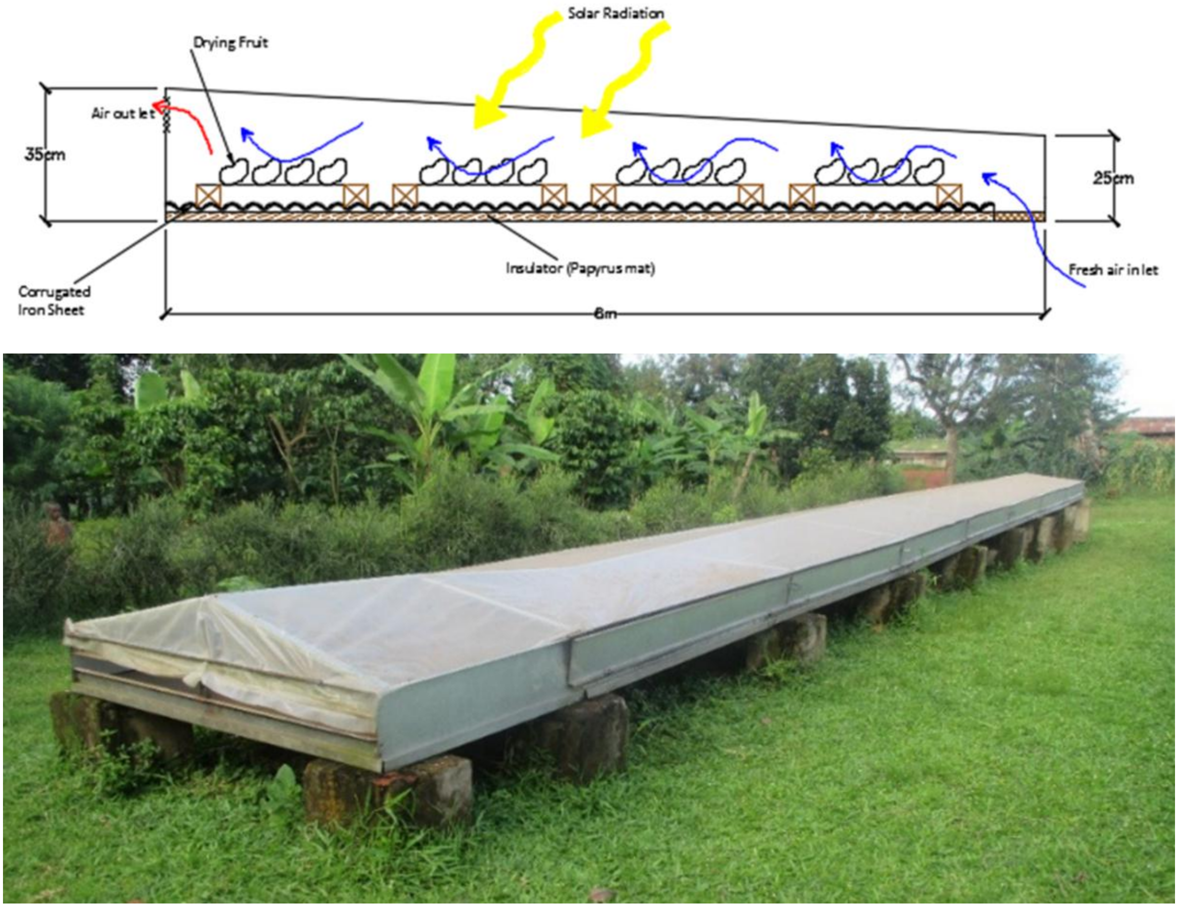

Figure 2 PPI tunnel solar dryer model (Credits Galyaki, C)

The NRI Kawanda cabinet solar dryer

This model is similar to the SBB solar dryer in construction. The frame work is made out of wood, the drying chamber is covered with a plastic sheeting (visqueen), and the bottom of the dryer made of corrugated iron sheets painted black (Figure 3). A papyrus mat underlays the iron sheet for insulation purposes. The dryer length is 4.4 m x 1.5 m width x 0.8 m depth. It has 6 trays made of plastic mesh fastened on wooden frames and relate to a drying capacity of 25 to 30 kg of fresh fruit slices per batch. The visqueen remains durable under harmful effects of relatively high ultraviolet light intensity and can be replaced every 2 to 3 years. In addition to the challenges of the SBB model, the presence of two trays, one above the other makes drying on lower trays slower because they do not receive sufficient radiation.

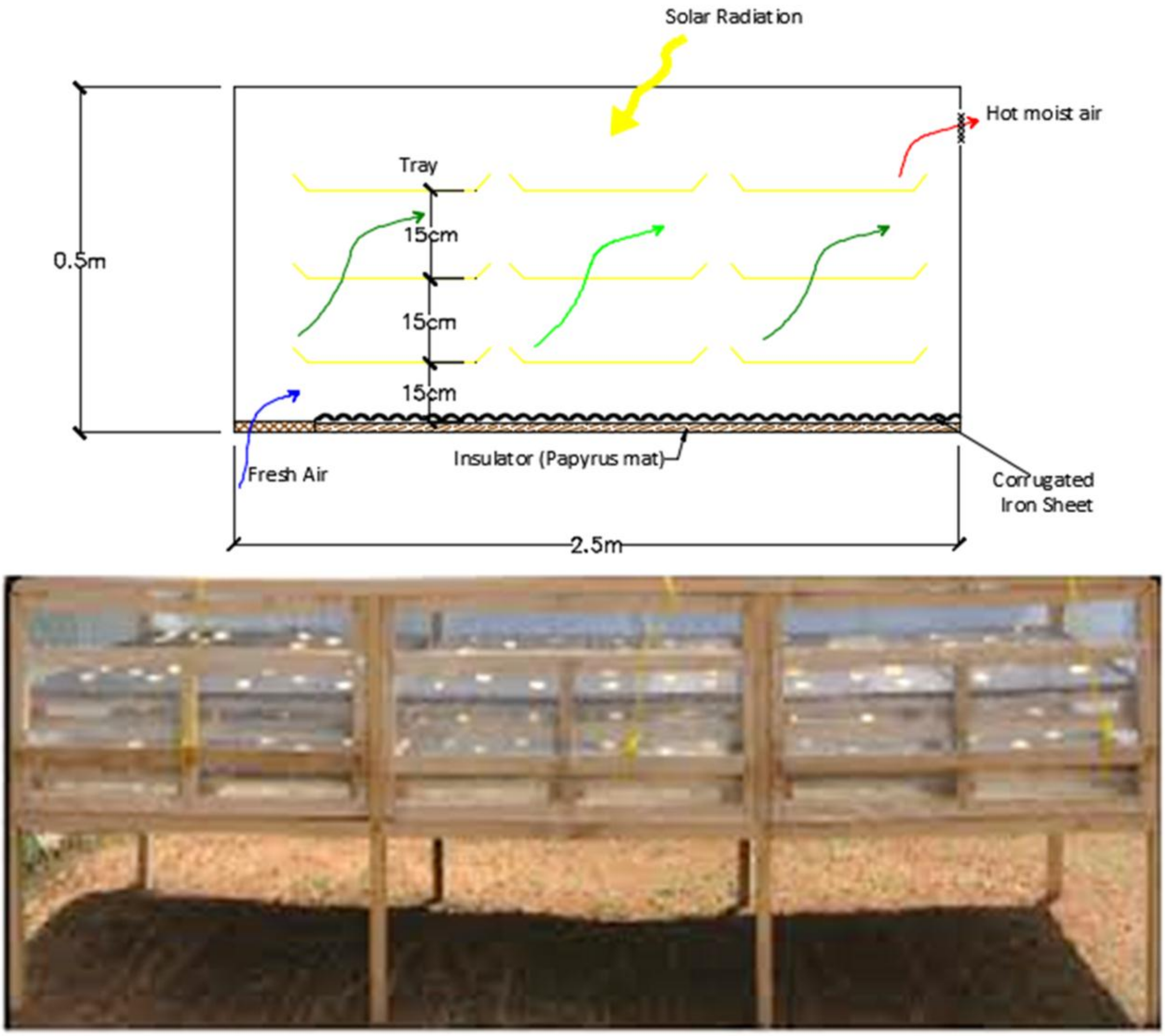

Figure 3 NRI Kawanda cabinet solar dryer (Wakjira et al., 2011)

The hybrid tunnel solar dryer

This model is made of a solar collector for preheating the air, a drying chamber, and a biomass air heating unit. The solar collector outer box is made out of wood, while the inside has a corrugated iron sheet painted black for maximum absorption of solar radiation. The top of the collector is covered with a piece of plastic sheeting. The walls of the drying chamber are made of wood and the top is covered with UV-stabilized polythene. Inside the drying chamber are trays made of UV stable mesh supported on wooden frames. The supplementary air heater is made of mild steel cylinder casing surrounded with a clay brick wall. The biomass burner has a chimney for ejection of exhaust gases high enough to eliminate contamination of drying produce. The dryer assembly is raised off the ground by clay brick pillars (Figure 4). Averagely, inside air temperatures are 47.3^{o}C±2.9^{o}C (with solar energy alone) and 52.1^{o}C±1.6^{o}C (when supplemented by the biomass heater). Relative humidity varies around 37.2^{o}C±1.4^{o}C. When the dryer relies solely on solar energy, it takes 2 to 3 days per batch while under hybrid mode, it takes a day. Although this model resolves the challenges related to fluctuating weather conditions, the use of biomass (e.g. wood and charcoal) still raise issues of environment and climate change and it is an additional cost to the users. Additionally, exporters of dried fruits raise concerns of contamination of the product by biomass burn off gases. Therefore, the model was not adopted by farmers and was found dilapidated at one drying site.

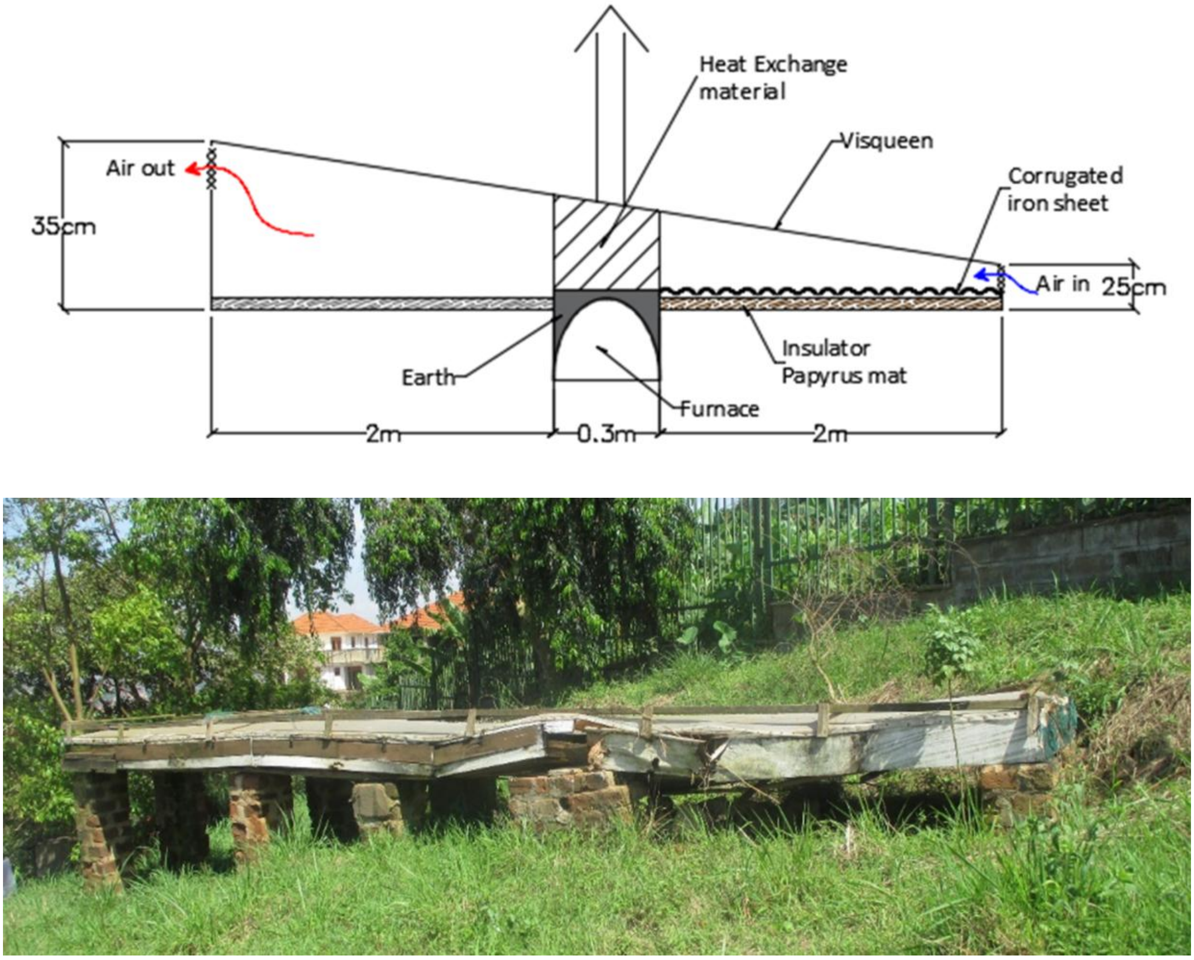

Figure 4 Hybrid tunnel solar dryer model (Credits Galyaki, C)

The UNIDO solar hybrid dryer model

The UNIDO solar hybrid dryer model shown in Figure 5 was born out the failures of the static bed type solar dryer. The dryer consists of a solar air heater, three drying chambers with drying trays, a photovoltaic system, a DC radio fan and a supplementary heater. The collector is made of aluminum expanded metal screen and a single piece of aluminum foil sheeting below. The collector top is covered by 4 mm thick colourless glass. Drying chambers are fabricated out of 20 mm thick wood with inner walls overlaid with aluminum foil to prevent contact of moisture carrying hot air with wooded walls. Each tray is made of 1 m^2 aluminum mesh supported on a wooden frame. Two fans of 350 m^3/h to 600 m^3/h are run by two 12 V lead acid battery of 120 Ah storage capacity, charged by two 50 W solar cell modules. The solar model is supplemented by a diesel fuelled indirect heater under bad weather conditions or at night. The supplementary heater consumes 2±0.5 L/h of diesel fuel. Heat inside the dryer is controlled by use of a thermostat. The dryer achieves drying air temperature of 45.0^{o}C±1.6^{o}C under solar energy alone and 54.6^{o}C±1.3^{o}C when supplemented by a diesel burner. Much as the UNIDO solar hybrid dryer solves some of the challenges presented by the static bed type solar dryer, such as poor solar energy tapping and plastic bag sweating, questionable quality and hygiene of the final product and proneness to larger pests attack and theft, the basic challenges of lack of control of the moisture of the final product, single crop dryer during a given cycle and over dependence on solar energy during the drying process remained. The UNIDO solar hybrid dryer also created an additional challenge of higher investment operation cost. As such the technology exists only where seed capital was advanced to farmers.

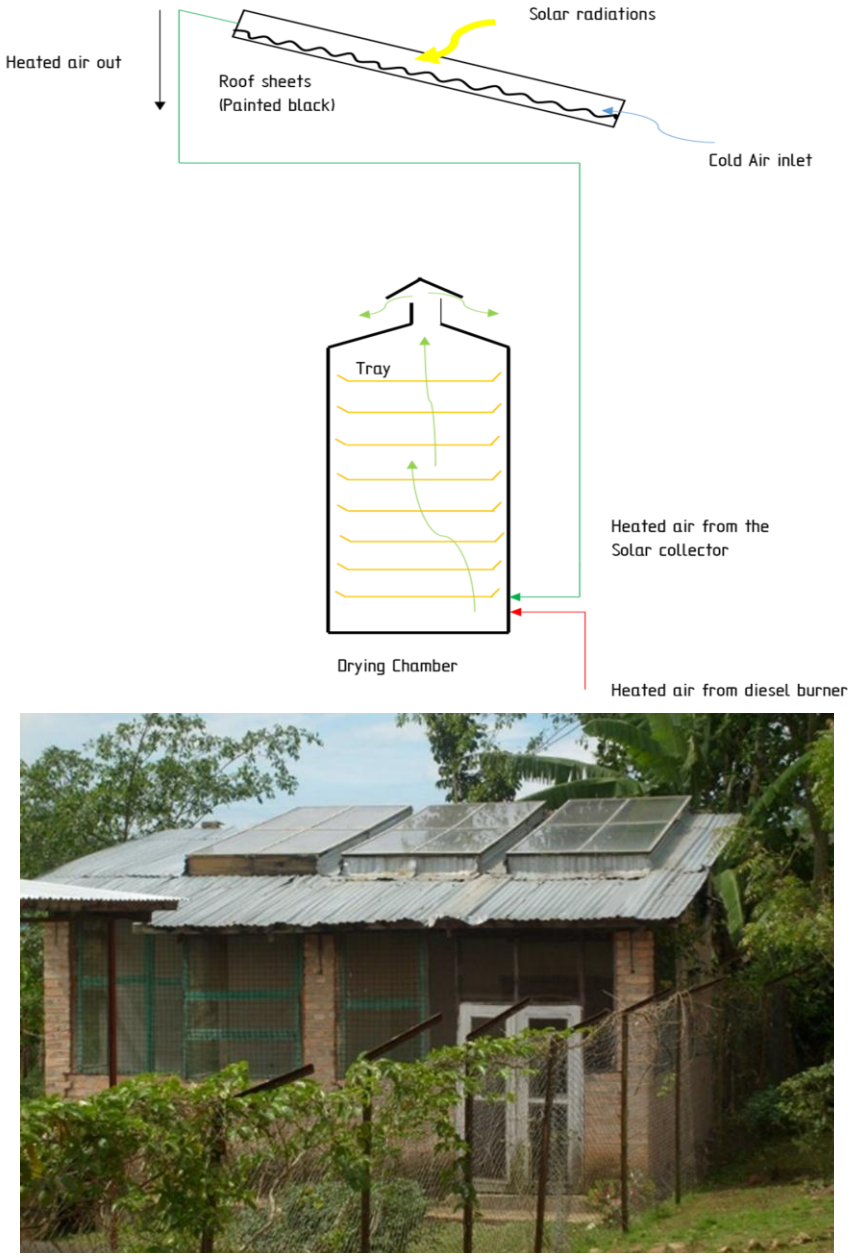

Figure 5 UNIDO Solar Hybrid dryer Model (Credits Galyaki, C)

3 Solutions to the identified design constraints

The SBB (Figure 1), PPI (Figure 2), NRI Kawanda cabinet dryer (Figure 3), and the Hybrid tunnel solar dryer (Figure 4) models can be retrofitted by incorporating DC fans powered by solar cell modules to improve extraction rates of the moisture carrying air. By increasing rates of driving out air that has been saturated by vapor from drying produce; drying rates can be improved with consequential reduction in drying time and increased product quality. Also, sweating of the plastic sheeting will be overcome, and therefore solar radiation penetration will be maximized. Moreover, heat and mass transfers inside the dryer will be improved and uniform batch produce drying can be achieved as a result. Alternatively, wind ventilators can be used to achieve better convection. Studies where fans or wind ventilation have been used (Mohanraj and Chandrasekar, 2009; Velmurugan et al., 2013; Toshniwal and Karale, 2013; Amedorme et al., 2013; Dejchanchaiwong et al., 2014) also affirmed that the derived improvement in flow of air increases drying rates and improves quality of the product. However, since installation of the equipment comes with an extra cost, designers should keep in mind the delicate balance between the costs and benefits for feasibility.

Furthermore, issues arising from material selection for example; the proneness of wood to rainy conditions and its ability to soak and develop moulds; use of paints potent in chemo-contamination of products, and use of meshes iron sheets that can rust, can be resolved by careful development of manuals with lists of locally available materials, their grades with respect to established food safety standards, indicating components of the dryer where these materials can be best utilized and specifying any precautions that may be necessary. Those who develop new designs or improve existing ones should provide outlines of construction details and provenance of materials used to allow precise reproducibility. A delicate balance between cost and sophistication must be attended to during material selection to increase affordability without compromise of set standards.

In addition to developing manuals with standards, the gap between experts in drying and crafts men, who are mostly engaged in dryer fabricating works can be bridged by developing simple design procedures. This will help eliminate or reduce difficulties faced in sizing and scaling solar dryers to meet anticipated production capacities and required drying rates and times. There is also need for training and demonstration of new technologies to; transfer technical information to local artisans and interest formers in adopting such innovations.

To avert the challenge of energy surges caused by unprecedented weather changes, use of thermal storage systems is now being adopted (Madhlopa and Ngwalo, 2007; Bal et al., 2010). Common storage materials for sensible heat include; water, gravel bed, sand, and clay among others (Mohanraj and Chandrasekar, 2009). Most of these materials are locally available and not costly. Thermal storage systems enable drying to continue after sunset provided there is enough sunshine during the day. Inclusion of heat storage material has been reported to increase the drying time by 2 to 4 drying hours per day (Mohanraj and Chandrasekar, 2009; Toshniwal and Karale, 2013). Ultimately, backup heating systems enhance consistent air temperature inside the dryer, substantially reduce the drying time and improve dryer thermal efficiency (Bena and Fuller, 2002; Madhlopa and Ngwalo, 2007).

Further, to reduce delays in drying rates and times caused by inefficient conversion of trapped solar energy into thermal energy (the required enthalpy), there is need to modify the collector plates. Collector plates can be improved by: using corrugated absorber plates instead of plane sheets (Al-Juamily et al., 2007); integrating collectors with house hold rooftops to increase collector area at a buffered cost (Janjai et al., 2008) and may lower cost for installation of the UNIDO model; using reflective walls to concentrate solar radiations (Sethi and Arora, 2009) and by increasing the retention time of air through the collector to allow adequate time for heating it and thus increasing the collector thermal efficiency (Othman et al., 2005; Sopian, et al., 2009).

Mass transfer and distribution of thermal and flow field inside the drying unit can be improved by firstly understanding patterns of these parameters during the design process, before construction and subsequent testing is imperative. This can be achieved through simulation. Simulations aid analysis of disturbance effects and provide consistent information for identifying system weakness and potential design improvement (Ingle et al., 2013). Several studies (Hossain et al., 2005a, 2005b; Amanlou and Zomorodian, 2010; Adeniyi et al., 2012; Kumar et al., 2012; Misha et al., 2013a, 2013b, 2013c) revealed that application of Computational Fluid Dynamics (CFD) analysis techniques to analyze distribution and transfer of heat and velocity fields is an inexpensive and less time consuming way to; optimize, retrofit, improve equipment and processing approaches. This is because CFD techniques precisely predict air flow distribution, temperature profiles, and momentum flow in the design of dryers and/ or drying systems. Dryer developers need integrate use of CFD their designs to prevent problems of poor heat air flow field distribution (Amanlou and

Zomorodia, 2010; Yunus and Al-Kayiem, 2013) and accruing lack of uniformity in product drying rate within the dryer.

4 Rethinking the solar fruit dryer

The findings of this review point to a need for multiple interventions with a purpose of developing a dryer tailored to needs of farmers and mainly products that meet the increasingly stringent product quality demands. Appropriate solar fruit dryers for smallholder should be elaborated and comprehensively designed covering the aspects indicated in Table 1. Such a dryer overcomes the limitations such as; low capacity, long drying time, unstable internal heat, limited utilization of solar energy, hygiene issues, affordability and ease with which the small scale farmers can replicate the technology and repair among others, which are critical challenges essentially preventing farmers from moving up a level in production and income generation.

Table 1 Design consideration and standards

Design considerations	Key Indicators
Locally appropriate	Affordable Local capacity to constructed, repair and maintain Easy to operate Optimally utilizes space
Should be a fully developed advanced design	Optimized With specifications Costings Detailed financial viability and payback analyses
Materials	Concur with food safety requirements Affordable Locally available Requires less skilled personnel Do not react when used with different produce of interest Not prone to environmental degradation
Provenance	It should have undergone a robust program of testing producing conclusive results that inform of the present and future of the system It should enhance resilience and viability of small producer businesses
Guidelines	Should have clear and practical guidelines for users

5 Conclusions and recommendations

5.1 Conclusions

From the critique of existing solar fruit drying technologies' designs in Uganda, the following can be inferred. Firstly, there is recognition of the importance of solar drying technologies in the small scale dried fruit producer industry. Secondly, evidence confirms that contrary to what is widely perceived, it is not humans that adapt to technology rather technology has to evolve in a manner that suits the human needs and conveniences. This calls for advancement and improvement of solar drying technologies, tailoring them to real time needs of farmers and consumers of the dried produce, and to simulate the near future needs. In addition, appropriateness of an improved solar drying system should be visible in terms of increased capacity of production, better quality of produce, easy to operate, and within the capacity of local technicians and craftsmen to precisely reproduce and maintain it. Improved solar dryers should translate into improved livelihood of farmer communities in terms of wealth enhancement and emancipation of women and children. Moreover, material selection has been cited as leader in influencing success of solar dryers. This is majorly because materials used determine the cost of acquiring and maintaining the dryer, durability, and safety aspects of food. Therefore, experts should observe the thin line between costs and benefits of selected materials. More still, all the dryers found in the field, apart from the UNIDO model, have some or all of the following challenges: lack of control of moisture content of the dried product, poor solar energy tapping due to placing of wet produce over the absorber plate and sweating of the visqueen, susceptibility to fluctuating weather conditions leading to unpredictable drying rates, inherent low capacity per batch, risk of mould growth on water soaked wood and papyrus, risk of contamination of drying produce by heavy metal elements from paints, and low durability. The UNIDO model shares some of the above challenges for example risk of mould growth on wooden wall of the drying chamber and lack of control of moisture although its main shortfalls are the intensive capital requirements and operation costs.

5.2 Recommendations

It is recommended to develop efficient and affordable designs using scientifically proven methods such as Computer Fluid Dynamics to pre-test and optimize the dryer, incorporating alternative energy sources in the design to ensure an all-weather dryer. In addition, there is need to develop simple manuals with standards and fabrication procedures, to ease reproducibility of solar fruit drying technologies, and materials selection during fabrication which is majorly done by local craftsmen with little knowledge on food safety standards. Although the use of paints on absorber plates of solar dryers is associated with contamination of dried produce, there is need to empirically evidence the level of contamination and risk involved in consuming the product.

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