Contents lists available at ScienceDirect

Cleaner and Circular Bioeconomy

journal homepage: www.elsevier.com/locate/clcb

Solar powered dryers in agricultural produce processing for sustainable rural development worldwide: A case study from Nayarit-Mexico

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ARTICLE INFO

Keywords:
Sustainable rural development
Solar photovoltaics
Solar drying
Renewable energy
Cleaner production
Circular economy

ABSTRACT

Nayarit state on the Mexican Pacific Coast has a land area of 27,850 km^2 and a coastline of 290 km. The state represents 1.4% of the national territory, of which 438,400 hectares are currently dedicated for agricultural use. Nayarit is home to 1.23 million people, and produces tropical fruits such as mango, 316, 750 metric tons and soursop 15,400 tons (May–July); pineapple, 34,250 tons (March–April); bananas 27,800 and jackfruit, 23,250 tons. Presently these add up to a total of 500,000 tons of yearly tropical fruit harvest amidst an increasing public awareness that these hold essential nutritional ingredients to help the population maintain its health and well-being. However, the water content in the produce of typically above 80% w/w, leads to bacterial and fungal activity. Consequently, a notable fraction of the produce perishes in a short period of time before they reach the consumer. Globally, such loss is 1.3 billion tons every year, as defined by the food loss index (FLI) and the food waste index (FWI). According to Sustainable Development Goal (SDG)-12 of the Food and Agricultural Organization (FAO), both FLI and FWI should be reduced to one-half its current levels by the year 2030. To meet this goal, a significant fraction of the farm produce may be set apart for drying in solar powered dryers at the farm-site. With an aperture of 36 m^2 each, letting in UV filtered solar radiation and with an electric grid-integrated PV system, we estimate that 3500 of such dryers can produce nearly 480,000 kg of dried farm produce per day. This production represents 25% of the harvest, recovering also a significant amount of potable water released from the produce while drying. Thus, rural areas would produce dried farm products utilizing renewable energy; supply these worldwide, and benefit themselves from sustainable development.

1. Introduction

Renewable energy consumption has the benefit of decreasing the dependence on fossil fuels and reducing the pollution levels. Thus, the use of renewable energy should be a priority for each country in developing its energy sustainability national plans to achieve Sustainable Development Goals (SDG) (Armin Razmjoo et al., 2019). Solar drying of farm products is essential toward achieving Sustainable Development Goals in rural communities in Mexico. Solar drying practices have evolved from the early humans to date, as mentioned in a 2011 review (Belessiotis and Delyannis, 2011). Modern solar dryers utilize solar photo-thermal converters, electric powered extractors, and solar photovoltaic extractors (Janjai et al., 2011), thereby making the drying process rapid. We reported that UV-Blue filtered solar drying may inhibit darkening of certain farm produce, which may improve consumer acceptance (Nair et al., 2020). When the fresh produce and solar-dried produce are displayed adequately at distribution-outlets or supermarkets, urban consumers can opt for fresh produce to consume soon and/or buy the dried produce to consume at one's convenience. Rehydrated dried fruits and fruit mixes mostly retain the original texture, color, flavor and nutritional values. Via solar drying of the farm produce, the Food Loss Index (FLI) and the Food Waste Index (FWI) are reduced. Thus, the same harvest meets the consumer demand. Farmland and water usages are practiced with efficacy, and the Water Foot Print (WFP) of the consumed produce is kept to a minimum. These steps contribute toward meeting the SDG-12 for 2030, as set by the Food and Agricultural Organization (FAO) on *Responsible farm production* and *Responsible consumption*. We present below the context of many basic aspects of this transdisciplinary study, and present the objective of this work. The specific case of Nayarit, an agricultural state in Mexico is chosen to illustrate

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https://doi.org/10.1016/j.clcb.2022.100027
Received 9 April 2022; Received in revised form 22 July 2022; Accepted 5 September 2022

a methodology for solar powered drying to lead toward “zero-emission” production and processing of agricultural farm produce to meet sustainable development. We consider that such methodology is applicable to rural areas in many countries.

2. Sustainable rural development—outlining the parameters to build a common awareness base

Most regions of the world now classified as “rural,” traditionally lead a sustainable lifestyle, in harmony with nature. Natural resources – land and water, were prudently managed with minimal loss or waste of farm produce. Organic manure and crop-rotation practices constantly replenished the soil with nutrients, and maintained the farm productivity nearly constant over the years. The industrial revolutions and the urbanization, which followed it, altered this rural life. Increased demand was placed on the rural regions for the farm produce to meet the changing urban lifestyle. “Green revolution” in the rural farm in the 1960′s, which was partly facilitated by genetically modified crop varieties (GMO’s) would face within 50 years the urban clients’ preference toward non-GMO produce. Chemical fertilizers introduced into the farms to increase their productivity would also face urban customer preference toward “organic produce.” The diesel-, electric- and even photovoltaic (PV) water-pumping would alter the sustainability of local water resource; it lowered the water level in the ground- and underground reserves at a rate surpassing the replenishment rate. Such practices added Carbon Foot Print (CFP) and WFP to the farm produce, which were soon noticed by international organizations as “unsustainable”. Consequently, urban customer preference shifted to low CFP and low WFP farm produce. Rural communities which passed through periods of expectations and desperations this way, now view sustainable rural development programs with disdain. During the present study, we recognized “sustainable rural development” as a transdisciplinary paradigm. Providing an outline of the parameters involved in this paradigm to build a common awareness base among all the parties involved is essential to develop a holistic approach to achieve tangible results in this theme. Some of these parameters are outlined below.

2.1. Plant based food and health benefits

Fruits, vegetables, and grains contain nutrients: carbohydrates, proteins, fats, vitamins, minerals, and various micronutrients, fiber – both soluble and insoluble, and a large proportion of water. The simultaneous availability of all of these in the food intake is essential for the balanced development of a healthy organism. The benefit to human health from plant-based food is widely recognized by now. Specifically, the fiber content benefits the proper functioning of the digestive and cardiovascular systems (Viuda-Martos et al., 2010) and flavonoids act as protective agents against degenerative diseases (Salehi et al., 2019). Benefit from an overall prophylactic/therapeutic action in a nutraceutical approach helps build a healthy body (Das and Biswas, 2016). Based on clinical studies, a plant-based diet is recommended for all those with high blood pressure, diabetes, cardiovascular disease, or obesity, thereby reducing healthcare costs and improving the overall well-being of a population (Tuso et al., 2013).

2.2. Agricultural farm produce and water foot-print (WFP)

Plant-based food is mainly sourced from the world’s rural areas. Here, the farming cycle culminating in the harvest season entails a large WFP for each product, discussed in (Hoekstra, 2008). For example, an estimated 1600 L of water is invested in producing each kg of mango once every year. Such a large value of WFP arises due to the evaporation of water from the mango leaves during the entire year. For example, ref. (Thwin et al., 2002) reported that water loss via transpiration is 20 to 70 mg/m^2 every second from mango leaves in the shade and under the sun, respectively. The gain in the biomass of the tree trunk is disregarded as a useful product in this estimation. The WFP of a product from plants carrying leaves over short periods is relatively low: 240 L for pumpkin or cucumber and 180 L per kg of tomato.

2.3. Food loss index and food waste index

Notable in plant-based food is also that the water content in the produce itself is typically more than 80% (Bastin, 1997). If a fresh produce is consumed adequately and soon, it helps maintain a healthy nutrition and hydration in the organism. However, the water content in the product is also why it rapidly perishes from bacterial and fungal actions before it is transported, delivered to the consumer and ingested. A perished produce implies a lack of nourishment in the intended consumer, which in the long run decreases the healthy life span of the individual and levies the health care system. Also this food loss implies a reduction in the income for the farmer, despite an effort to overcome the food loss through production from an increased land area. Also, the water invested for the production has become in vain, which impedes achieving SDG’s. In a 2011 survey, the Food and Agricultural Organization (FAO) of the United Nations placed the loss or wastage of farm produce meant for human consumption at a factor of one-third, amounting to 1300 million tons per year globally at the time. The food loss index defines the loss at the production and distribution side – FLI (the fraction or% of food lost); and the food wastage index defines the wastage at the consumer end – FWI (the fraction or% of food wasted). Reduction of both these indices requires attention to achieve sustainability in farm production. Reduction of FLI and FWI by 2030 to half their 2011 level is cited as the SDG-12 of FAO, launched in the year 2020. Thereby, the year 2021 was designated as “The International Year of Fruits and Vegetables - Fruits and Vegetables - Your Dietary Essentials” (FAO. 2020).

2.4. Drying of farm produce to reduce FLI and the carbon foot print (CFP)

To meet SDG-12, part of the farm produce may be directed to drying at the farm site, which would bring down the FLI at the production site and during its transportation, with an influence to bring down FWI at the distribution and consumer end as well. However, drying of the farm products implies the evaporation of its water content at an energy input of 2.26 MJ per kg of the evaporated water. This value is the latent heat of vaporization of water (Wilson, 1994). Thus, it involves typically 9 MJ (2.5 kWh; 1 kWh = 3.6 MJ) of energy to yield 1 kg of the dried produce. At an electric dryer efficiency of 70%, the energy requirement is 3.57 kWh per kg of dried produce. For a typical energy mix of 85% from fossil fuel, fed to the national electric grid (in the case of Mexico), the CO_2 emission equivalent (0.35 kg CO_2– eq./kWh) added to the ambient per kg of electric-dried produce, is 1.25 kg CO_2– eq. This is the “carbon footprint - CFP” introduced into the electric dried-produce. A similar value of CFP may incur in gas-fired, diesel-electric powered, or oven-dried produce.

Some rural farm sites may be located far away from the electric grid, but in many cases these may be accessible under the rural electrification drives launched in many countries. If the fresh produce is transported (by burning fossil fuel) from the farm to an electric food-drying facility located far away, the CPF adds-on, bringing it to nearly 2.9 CO_2– eq. per kg of the dried produce (Moult et al., 2018). A large-scale drying of 100,000 tons of fresh produce (20,000 tons of dried produce) per season implies the emission of nearly 60,000 tons CO_2–eq. They are added to the atmosphere, thereby failing to meet other SDG goals concerning CFP, even though a reduction in FLI and FWI of SDG-12 may be met.

2.5. Solar drying of farm produce to achieve simultaneous reductions in FLI, CFP, FWI, and WFP

Most tropical farms are blessed with abundant solar radiation, bringing in an average of 18 MJ/m^2/day (5 kWh/m^2/day) of solar energy resource at the site. Such abundance of energy is double the energy of 9 MJ required to dry 5 kg of the fresh produce spread over 1 m^2, mentioned above. When the solar drying of the produce is done within the proximity of the farm site, the CFP is reduced considerably. Basic criteria to secure food safety and the retention of nutritional value in the dried product have been given ample attention by the FAO over the years (FAO-AGS 2007; FAO. 2007). Drying of the produce at the farm site translates to a reduction in the FLI at the farm. It also creates local jobs. The shelf life of the produce in its dried version increases toward 12 months if the water content remaining in the dried produce is reduced to just above its equilibrium level. The CFP is reduced because the dried produce weighs one-fifth of the fresh produce. Lighter vehicles can carry the dried products from the farm site to the distribution centers situated nationally or internationally. The increased shelf life brings down food waste FWI at the distribution centers or in the consumers' homes.

2.6. Sustainable rural development achieved via solar drying of the farm produce

In Mexico (or elsewhere), the reluctance of rural communities to accept renewable energy technologies in farm production or processing poses a major impediment to rural development initiatives. It is essential to include in technological projects the social participants focused on bringing real solutions to socio-environmental problems by promoting shared responsibilities. While setting specific SDG, communities or countries require first to identify and establish the following characteristics and then develop methodologies to achieve them (Geissdoerfer et al., 2017):

(i) What should be developed? For SDG-12, plant-based farm food for all, with minimized FLI, and FWI.
(ii) What should be sustained? Water, air and soil in the rural farmland by minimizing WFP and CFP.
(iii) For how long? With an ever-increasing number of consumers aware of the health benefit and well-being from an adequate intake of plant based farm produce (Nair et al., 2020; Viuda-Martos et al., 2010; Salehi et al., 2019), the sustained demand for farm produce is poised to continue indefinitely.
(iv) For the benefit of whom? To benefit the people in the rural farm land, which eventually permeates to all the population and help build sustainable development.

Quests for sustainability, for food security, and the need to decouple food prices from fluctuating prices of finite fossil fuels are the drivers to sustainable processing and storage of agricultural products. Farming predominantly takes place in rural areas where conventional energy technologies may either be expensive or sometimes technically difficult to procure. Thus, deployment of renewable energy technologies to remote areas for sustainable power generation, cooling and drying of agricultural product becomes a necessity. Renewable energy systems, e.g., solar dryers, solar hybrid dryers, combined power and drying systems take leading roles in sustainable drying of farm produce (Lamidi et al., 2019). The dried products offer cheaper and safer methods to conserve food and distribute to rural and urban populations (Clausen and Rudolph, 2020). In the face of a great demand for food to feed world population, it is sad to note that 30–40% of the produced food perishes around the world every year due to a lack of adequate post-harvest processing and preservation.

In Mexico, the food waste index is 259 kg/*per-capit*a, and worldwide data indicates that 1300 million tons of food for human consumption are wasted annually (CEC, 2017).

3. Setting the objectives and methodology for this work

A growing population and unequal wealth distribution in developing countries have left behind a section of the society with ever-shrinking hope for betterment. Access to renewable energy services in rural communities gives added value to farm produce, which may lead to economically and environmentally sustainable agricultural activity. The well-being of rural population would set-in, with the benefits also translated to the urban sector, thereby making overall sustainable national development possible. It is gratifying to note that as a great contribution of science to humanity, by the year 2020, commercial photovoltaic (PV) modules have dropped in price by 500 times from an initial reference price in 1976, discussed in a "2020 PV Roadmap" (L. Wilson et al., 2020). The excellence of the yearly drop in module prices of 40% during the years 2006 to 2019 is in that it accompanied an improvement in the conversion efficiency of commercial PV modules toward 20% from about 10% in the 1980′s. A notable reduction in the degradation of this efficiency, by not more than 0.5% of the rated power per year was also achieved. Hence, the perspectives for grid-connected or stand-alone solar PV systems for rural sustainability through agricultural farm production and produce processing is brighter now in 2022 than ever before. The recent awareness on the need for eating plant based wholefood with a "rainbow of colors" (Meszaros, 2020) to boost immunity against infections, and specifically against Corona virus (COVID-19) (Arshad et al., 2020; Chowdhury et al., 2020) has brought agricultural farming communities as the vital building block for sustainable development through a healthy living for all the population. Overall, perspective for sustainable rural development that exists now, was not clearly evident and in public view in any pre-2019 period.

The objective of this work is to build up a methodology toward achieving this objective by identifying obstacles, highlighting opportunities, and accepting the need for a transdisciplinary approach to meet the goal by considering the specific case of Nayarit state. This work was initiated through the Phase I of a project (CONACYT, Mexico 315171, 2020 – '21) which carried a survey, "Energy-poverty and alimentary-need diagnostics in rural communities of Nayarit State." For this study we analyzed the case of seven representative localities, of five of the six distinct geographical zones of the state. This report is cited as Supplementary Information – 1 (Spanish version) in the present work. These localities varied in population of 240 to 2979 inhabitants. Upon the conclusion of this survey, we realized that we should seek methodologies to lead to sustainable socioeconomic development of the localities, based on the awareness base set in Section 2.

The references (Armin Razmjoo et al., 2019; Belessiotis and Delyannis, 2011; Janjai et al., 2011; Nair et al., 2020; Viuda-Martos et al., 2010; Salehi et al., 2019; Das and Biswas, 2016; Tuso et al., 2013; Hoekstra, 2008; Thwin et al., 2002; Bastin, 1997; FAO. 2020; Wilson, 1994; Moult et al., 2018; FAO-AGS 2007; FAO. 2007; Geissdoerfer et al., 2017; Lamidi et al., 2019; Clausen and Rudolph, 2020; CEC, 2017; Wilson et al., 2020; Meszaros, 2020; Arshad et al., 2020) cited in the discussion above illustrates the multidisciplinary nature of the present work. A bottom-up systems approach to orient science towards community development emerged in the 1970′s. The transdisciplinary projects require intense and sustained communication between all the parties and their continuous adaptation to emerging realities at the chosen location. It is vital to identify the specific technical knowledge applicable to a situation to create an opportunity.

This approach consists of the following stages:

i) Identification and structuring of the problems.
ii) Investigation into these problems to gain in-depth understanding.
iii) Transformation of the problems into opportunities by developing methodologies.
iv) Implementation of methodologies, evaluation of the outcome, and restructuring of the methodologies to ensure sustainability.

Thus, it implies that the object of study can be approached by various disciplines and stakeholders that interrelate and intercept each other with their knowledge, explanations, and interpretations (Mallee, 2020). It may be possible to move towards prosperity and well-being of the communities and promote the successful implementation of sustainable energy systems based on solar thermal and solar photovoltaic technologies to supply their energy requirements. Renewable energy offers opportunity to vitalize rural areas and overcome the uneven development of national resources (Stauffacher et al., 2006). We apply our awareness of the SDG to Nayarit, México. The specific climatic features of Nayarit and a high level of electric grid penetration in the rural sectors of this state, lead us to suggest grid-connected photovoltaic (PV) powered drying systems here. We illustrate in Section 6, and sum-up in the Conclusions, that this approach may be adaptable to other farming regions in the world.

4. Methods

This work spans across solar energy resource evaluation, tropical farm production estimates, the energetics of the produce drying process, reliable assessment of the prevailing perception of rural communities on renewable energy technologies for profitability in farming practices, and sustainable aspects of solar drying of the farm produce *at the site* by integrating recent research results. We present the validation of predicted solar energy availability data in the State of Nayarit in Mexico to enable large-scale solar drying projects. Solar drying gives added value to the farm produce of small rural communities in Nayarit, with a view to meet sustainable development goals. For this study in Nayarit, the choice of locations were subjected to the selection criteria:

(i) A community size between 200 and 3000 inhabitants.
(ii) An agricultural production occurring at a level above that of self-consumption.
(iii) Accessibility by road; and
(iv) Availability in the community of an individual with technical skills, and interested in the community development.

We also considered the community's solar resource availability at a level equal to or greater than the national average.

A 9-year long monitoring of the electric energy output from a 2.4 kW-peak (kW_p) PV system interconnected to the grid at the state capital Tepic, illustrates the system characteristics and reliability. Such systems may be scaled-up and integrated into solar powered produce drying units in the state. In Section 6 we discuss the features of such dryer systems involving photothermal (PT) – photovoltaic (PV) conversion of solar energy and UV-Blue filtered solar dryer technology set at the farm site. Together, these provide clean-processing of the products. The following aspects of the methodology are worth highlighting:

(a) This work is based on ethnographic interviews and observations on rural Nayarit, joined with social actors of each locality (Supplementary Information 1). We applied a structured quiz as well as interviews based on a semi-structured script to a convenience sample by applying a rapport technique, which establishes a dialogue with connection, and successful communication based on mutual respect, thereby generating the environment of trust, conducted by research groups whose task is to develop energy-based rural development models. The research group has members belonging to the communities.
(b) We establish the feasibility of introducing solar drying systems for the farm produce, based on the abundance of solar energy in the state and the abundance of tropical fruits in this state.
(c) The solar energy availability was confirmed by actual system performance data for the past 9 years (2012–2020) at the site.
(d) Based on (a) to (b) we propose technical and process flow schematics on "near-zero waste" and "near-zero emission" solar powered drying systems.
(e) We then generalize the benefit of these systems for rural agricultural societies globally to achieve sustainable development.

5. Results and discussion

5.1. Data for Nayarit state, Mexico relevant to sustainable rural development through renewable energy integration in farm production and produce processing

Centered at 21°45 N 105°14′ W, Nayarit, illustrated in Fig. 1, has a Pacific Coastline of 290 km; a land area of 27,850 sq. km (2785,000 hectares); and a population of 1.235 million people (2020 census). As of today, 5% of its population speaks native languages. This is an agricultural state supplying its products to large capital cities of Mexico and also exports them. The state has diverse characteristics in terms of climate, soil types, and topography even at the municipal level. Thus, extensive variation in agricultural produce is typical here. The state territory is classified into six economic and geographic regions: North, Center, South, South Coast, Sierra (Mountain), and North Coast (Fig. 1). The state comprises of 20 municipalities, organized/classified into 2850 *ejidal* (farming) and communal localities. Of these, 2793 are rural, accounting for 28% of the population. Only 57 of the localities are urban, but they represent 72% of the population.

Nayarit state is suitable to test whether the integration of renewable energy technologies in agricultural farming activities can have a measurable impact on its socioeconomic development. The state is placed 29th from the top in population among the 32 federal states of Mexico; 23rd in land area by occupying 1.42% of the national territory (of 1.97 million square km total). The gross domestic product (GDP) per capita of US$ 6000 (approx.) estimated for 2020 is 70% of the national average (INEGI 2021). However, this GDP is only 35% of the Mexican states with large industrial manufacturing activities. Not surprisingly, the state GDP is comparable with those of other Mexican states, where agricultural farming forms the major component contributing toward their state GDP. In *human development index*, (HDI) of the United Nations Development Program (UNDP 2020), Nayarit is assigned with a HDI of 0.776, and is 16th among the 32 states. The lag in GDP of agricultural states compared with states with manufacturing industries is a global occurrence. Among the reasons for such a lag in the GDP is the loss of agricultural produce at the farm site from abundant harvest or during transportation before it reaches a manufacturing/processing /distribution site in a city. This situation can change if the processing is done at the farm site. When the energy required to do this comes from renewable sources, such as solar, the zero-emission and minimum loss goals are met in a sustainable manner.

Energy from PV systems is noteworthy for rural farming because of their modular scale-up capability to meet changing local needs. The rapid reduction in PV system costs in recent years offers a unique opportunity now, which did not exist previously (Wilson et al., 2020). The PV module cost has dropped from above US$100 per peak-watt ($W_p$) in the year 1976 to below US$0.2, by 2020. This updated information has not permeated adequately to rural communities, where small PV units for lighting or water pumping were introduced in the 1990′s when the system costs made these inaccessible, unless through national or international financial schemes.

"Direct Solar Drying" as a means of conserving tuber crops, grains, pulses, berries, fruits and vegetables for the post-harvest season has been practiced over the years in rural communities, and therefore it does not hold any novelty by itself. However, the unpredictability of solar radiation during the harvest season, which can overlap with the rainy season in some areas, requires labor-intensive operations to protect the drying produce. Infestation by pests during drying of products leads to a lack of consumer confidence in their consumption. Over the years, these limitations caused the slow migration of produce drying in the farming region to centralized processing facilities, which use drying ovens powered by burning fossil fuel or by grid-supplied electricity, with a high fossil fuel component in its generation. The knowledge of heat and mass transfer has promoted the design of more efficient so-

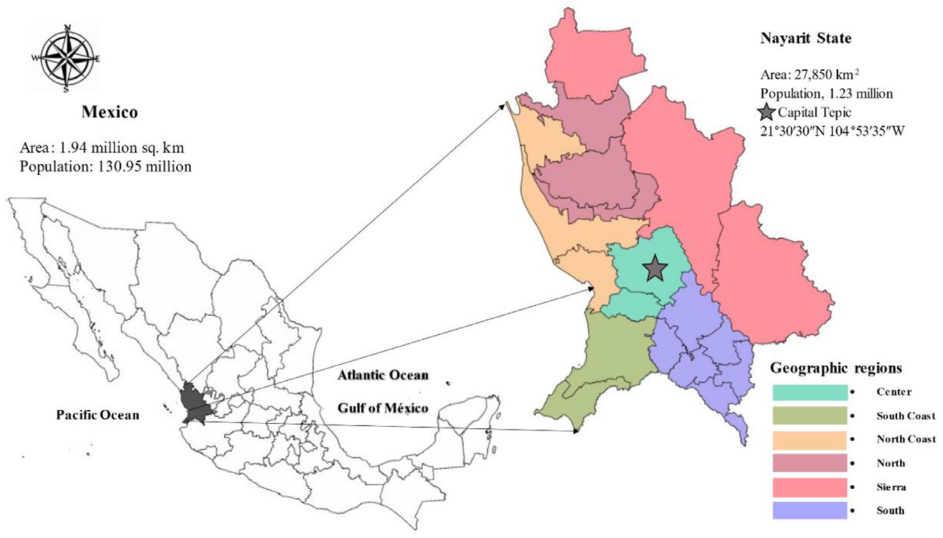


Fig. 1. Map of Nayarit State, Mexico and the geographic and economic regions of Nayarit State (INEGI, Mexico, 2021). Sierra is mountainous region. (Details in Supplementary Information – 1).

lar drying ovens (Belessiotis and Delyannis, 2011). Sometimes they are of a hybrid version utilizing grid-electric power to promote convective heat transfer (El-Shiatry et al., 1991) or by integrating solar PV power to facilitate expulsion of water vapor from greenhouse-type industrial-scale farm produce drying (Janjai et al., 2011). Solar drying of farm produce forms a special part within the solar drying processes, which may include drying of industrial raw materials and products including woodchips and leather. In the case of drying of farm produce – either as fruits or vegetables or their slices or pulp, the FAO drying manuals (FAO-AGS 2007; FAO. 2007) suggest the importance to maintain the temperature of the produce being dried to preferably within 35–55 °C to minimize losses in nutritional components in the dried product. Drying under a shade instead of in direct sunlight is suggested for some farm produce to conserve food texture, color and nutritional value. The UV-Blue filtered solar drying using spectrally selective optical coatings to conserve color (Nair et al., 2020) is an innovation introduced in the year 2020. By using a choice of plastic glazing sheets (Rodríguez-Ramírez et al., 2021) or with edible coatings as a thin cover over sliced produce (López-Ortiz et al., 2021) have shown the different extent of retention of polyphenols and anthocyanins in strawberries, depending on the drying conditions.

In the following sections, we first present the fruit production estimates for Nayarit. We shall analyze the solar resource in the state based on predicted data for different economic zones using a freeware simulation program. Measured data for the period 2012–2020 is available from the data processing hub for a 2.4 kW_p PV system installed in the state capital, Tepic, at the state university site. Then we describe the energetics in setting apart 25% of the farm produce for drying. We survey how the farm producers view the renewable energy technologies. A notable level of skepticism was expressed by the communities in the farm sites to our survey team which included someone belonging to the same locality. The visits established that it is vital to build-up confidence level within the communities for the acceptance of these technologies. An assurance on sustained economic benefit to the farming communities is of fundamental importance. While analyzing the reduced solar resource and its intermittency during the peak harvest season in the May – July period in Nayarit, we conclude that a grid-connected PV system is an affordable option to meet "zero emission" production and processing of the produce at or near the farm sites in Nayarit. In Section 4, we present the schematics of such an initiative – on setting up of nearly 3500 grid-connected solar drying units in the state to meet the task of drying 25% of the farm produce to lead to sustainable socioeconomic development in the farming regions of the state.

5.2. Tropical fruit harvest in Nayarit-Mexico and potential for their dehydration to reduce food loss and food waste (FLW) indices

It is difficult to collect reliable data on the food wasted at the retail and consumption stage, because retailer strategies and consumer habits vary on how they deal with food liable to perish. Easier is to obtain estimate for the percentage of food lost after harvest at the farm or during its transport, storage, and processing. This stands at 13.8% globally. Reducing food loss and food waste (FLW) is vital to meet the SDG-12. The FAO has declared 2021 as the year of Fruits and Vegetables, recommending that sufficient intake of fruit and vegetable builds immunity to survive viral diseases (FAO. 2020), including the present day viral pandemic (Arshad et al., 2020). According to the World Health Organization, healthy foods and hydration are vital to an organism. Individuals consuming a well-balanced diet are generally healthier with a strong immune system and they hold reduced risk of developing chronic illness and infectious diseases (Tuso et al., 2013). Vitamins and minerals are also essential. Vitamin B, insoluble in water, protects the body from many infections. Vitamin C protects from "flu-like" symptoms. Insufficient vitamin D and vitamin E can lead to viral infections. Vitamin D can be found in sunlight, and vitamin E can be found in, for example, oil, seeds, and fruits. Therefore, in a regular meal, individuals should eat fruit, vegetables, legumes, nuts, whole grains, and food from animal sources (Das and Biswas, 2016). Thus, farm production generally done in rural sites can help build human health nationally. To achieve such a goal, the produce is made available in a sustained manner during post-harvest months. In turn, the rural community stands to gain from fair economic returns on their farming activity – an approach to improve the GDP and the HDI locally, and adding up at the national level.

Among the fruits produced in Nayarit with a demand in the international market are: soursop, jackfruit, mango, pineapple, banana, watermelon, coconut, and blueberry. Crops such as melon, guava, strawberries, blackberry, peach, and *tejocote* stand out at the state level. Nayarit has also a notable production of sugar cane, maize, sorghum, beans, and avocado. All these make Nayarit an "agricultural state." Table 1 provides the yearly production of some selected fruit crops in Nayarit, suitable for setting apart its 25% toward transforming these as solar dried products for worldwide marketing.

Production estimate listed here is prepared from published data available for the years 2017–2020 (SADER 2021). With the availability of the solar drying option for these fruits at the farm site and with the marketing advantage of "zero emission" agricultural products, the farm production may increase into the future.

Table 1
Annual production of fruits by volume and the national ranking for Nayarit state, Mexico, showing best values reported among the years 2017–2020.

Agricultural crop from Nayarit	Volume metric tons; 1 ton = 1000 kg	Mexican National Ranking
Soursop	15,417	1
Jackfruit	23,251	2
Mango	316,747	3
Avocado	67,059	4
Watermelon	51,944	6
Pineapple	34,252	6
Coconut	10,605	9
Banana	33,952	10
Blueberry	44	10

Nayarit's fertile soil and climate are conducive to an ever-increasing variety of fruits. Jack fruit, introduced in the year 1985 reached an annual production of 60,000 tons in 2020. However, the trees in this (or any) tropical location maintain the leaves all-year round, leading to transpiration loss and incurring a water footprint (WFP) estimated at 1600 L of water for each kg of mango produced at the farm (Hoekstra, 2008). Because of large-volume harvest occurring in a short period (60–90 days), peaking at 6000 tons per day for mango, a large fraction of the tropical produce is lost, wasted, or discarded before it reaches the consumer. Thus, the farm produce fails to meet the individual's alimentation and nutritional benefits it can offer nationally. FAO estimates that the loss at the farm and waste at the consumer end is about one-third of the worldwide overall agricultural farm produce. Hence, a target has been set to reduce such loss to one-half of its 2011 level by the year 2030 (CEC, 2017; FAO., 2020). The perished food increases the WFP of the utilized produce, requiring increased land and water use to meet the demand at the consumer end. It also lowers the farm income and makes sustainable goals unachievable.

Fig. 2 illustrates the basic approach in the hydration of dried fruit mix, by allowing to constitute a nutritional food supplement, which can provide to individuals vitamins, minerals, dietary fibres, and antioxidants in addition to carbohydrates, proteins and fat.

One may identify pineapple, mango, jackfruit, banana, melon, watermelon, coconut in the serving, Fig. 2c). A typical serving of many of the fresh fruit is considered as 150 g of slices or pulp (Ashfield-Watt et al., 2004). Many governmental agencies have data bases on the nutritional contents of fruits and vegetables, such as in: Food Data Central, US Department of Agriculture (U.S. Department of Agriculture 2021). Table 2 shows the typical nutritional content of 100 g of some fresh fruit (slice or pulp) produce at their recommended ripening level and seen among the dehydrated produce in Fig. 2a) and its rehydrated serving in Fig. 2c). It is known that the nutritional values of a produce varies with the ripening level, for example in mango (Sagar and Khurdiya, 1996), as well as during its drying (Rodríguez-Ramírez et al., 2021; López-Ortiz et al., 2021; Santos and Silva, 2008) and storage or processing (Perkins-Veazie et al., 2012). Thus, the information in Table 2 serves only as a guideline.

Dried fruits illustrated in Fig. 2a) are currently produced in Nayarit State in industrial ovens using liquid petroleum gas (LPG) as fuel and hence accompanied by CO_2 emission. Extractors powered by grid-electricity are installed to expel the water content from the drying produce, but without recovering it by condensation. Such recovery would be nearly 70 kg (L) of water per 100 kg of produce being dried. Most producers are willing to move toward renewable energy dryers if the "zero emission" processing brings-in sustained economic benefits through a certification process. The certification on "renewable energy processed product" brings-in marketing advantage from trade policies promoted by governments and "environmentally conscious consumers." In the sections below we present a methodology to transit toward such a goal, which consists of:

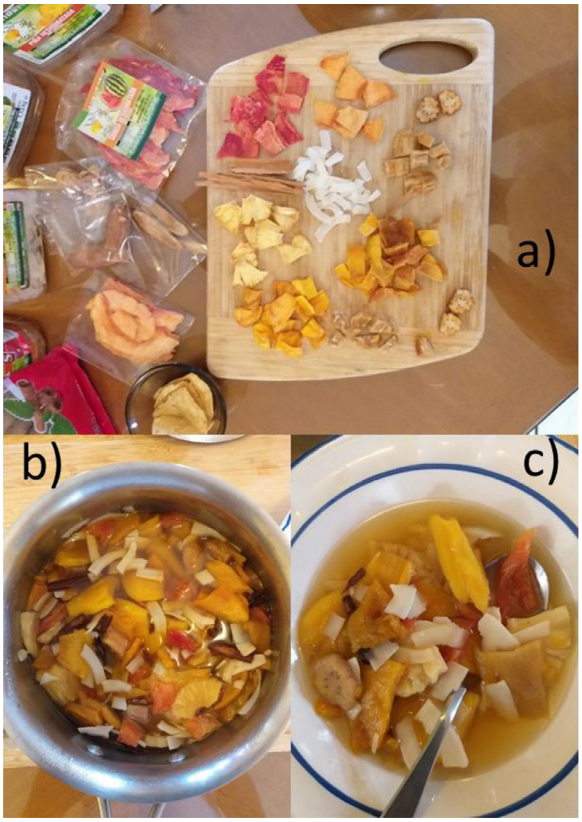


Fig. 2. Constituting a nutritional food supplement as seen in c), by hydrating dry fruits in warm water for 15 min, b). The dried tropical fruit mix shown in a) can come in single or multiple ration sachets. These fruit slices were processed in Nayarit State-Mexico in fossil-fuel fired industrial ovens using grid-electric powered water vapor expellers. Solar powered dryers with grid-connected PV systems can replace such dryers, as proposed in Section 6 of this work. Here each 30 g of the dried fruit slices in a) represents nearly 150 g of the fresh produce slices considered as a "serving size" (Ashfield-Watt et al., 2004). Thus, 120 g of dried slices seen in b) being hydrated in 1 L of water, produces 4 servings, each one as shown in c) in 250 mL of water.

(i) Evaluation of solar energy resource and its reliability in the farming regions.
(ii) Consideration of the energetics of solar dryers to arrive at a suitable solar powered drying technology for Nayarit.
(iii) Survey of the perception of the farming community to accept this drying system for their produce to agree upon a right approach to achieve the goal of solar powered produce dryers for sustainable development of rural farming regions.

5.3. Solar resource and photovoltaic system performance predicted using PVGIS software

Photovoltaic Geographical Information System portal (PVGIS-NSRDB) uses the National Renewable Energy Laboratory (NREL) data base and the National Solar Radiation Database (Huld et al., 2012). The PVGIS simulation program has been continuously improved by linking many databases and by improving the algorithms to enhance spatial resolutions and reliability of the predicted data. By now, these databases contain historical information on ambient temperature, relative humidity, global, beam, diffuse and infrared irradiance, wind speed, and atmospheric pressure. For the period of 2005–2016, an hourly measurement of each parameter was recorded during each day. The average over such a period represents the values for typical meteorological year. Selected communities living in localities belonging to the geographic regions are identified in Fig. 1. They are: San José de Motaje (North), Tecuitata

Table 2

Nutritional data for 100 g of fresh produce fruit slices at their recommended ripening level available from free access sites (USDA). The perceived health benefits may be found in institutional sites: Linus Pauling Institute (Oregon State University 2021). RDI: Recommended Dietary Intake.

Fruit	Nutritional content	Perceived benefits
Soursop; Jackfruit	Calories: 66 kcal, Protein: 1 g, Carbs: 16.8 g Fiber: 3.3 g, Vitamin C: 30% of RDI Potassium: 8%, Magnesium:5%, Thiamine:5%; Calories: 95 kcal, Carbs: 23.3 g Fiber: 1.6 g, Calcium: 3% of RDI Vitamin C: 21% of the RDI, Potassium: 13%, Phosphorous: 3%	Contains niacin, riboflavin, folate, and iron. Increases intestinal flora and reduces hyperacidity; Rich in antioxidants and omega-3, essential for healthy bone and heart. Contains Vitamin B1.
Mango	Calories: 63.7 kcal, Protein: 40 mg, Carbs:17.28 g Fiber: 1.06 g, Vitamin A: 29% of RDI, Vitamin C: 30%, Potassium: 5%	Helps immune system, vision and heart; promotes digestion
Pineapple	Calories: 50 kcal, Carbs:13.2 g, Fiber: 1.5 g Calcium: 3.2% of RDI, Vitamin C: 53% Potassium: 8.8%, Phosphorous: 1.4%	Contains lutein and β-carotene that help vision and skin
Banana	Calories: 89 kcal, Protein: 1 g, Carbs: 22.84 g Fiber: 2.6 g, Vitamin C: 11.6% of RDI Phosphorus: 3.2%, Potasium:10.2% Magnesium:6.5%, Potassium: 29%	Contains iron, niacin, tryptophan and Vitamin A, all essential for health
Melon	Calories: 36 kcal, Carbs: 9 g Fiber: 0.8 g, Calcium: 3% of RDI, Vitamin C: 20% Potassium: 6.5%, Magnesium: 2.4%	Contains high levels of beta-carotene; strengthens immune system; improves cardiovascular health
Coconut	Calories: 354 kcal, Carbs: 15 g, Protein: 3 g, Fiber: 9 g Fat: 33 g, Manganese: 75% RDI, Copper: 28%, Selenium: 14%, Magnesium: 8%, Phosphorus: 11%, Iron: 13%, Potassium: 10%	Medium chain triglycerides in the coconut fat promotes body fat loss

Table 3

Localities of farming communities in Nayarit state selected for the viability study for solar powered produce drying; number of inhabitants (2020 Census, and July 2021); Geographic location – longitude-West, latitude-North, altitude (m) above the mean sea level; Municipality and Geographic region. Nayarit takes its name from Nayar, a sixteenth century governor of the Cora people, who live in the locality listed last.

Locality; Farming	Inhabitants	Location	Municipality, Region
San José de Motaje; Maize	240	105°14′47″ W, l22°23′52″ N,100 m	Acaponeta, NORTH
Tecuitata; Mango, Jackfruit	382	105°08′44″ W, 21°27′06.78″ N, 219 m	San Blas, NORTH COAST
Tequilita; Maize; Vegetables	638	104°47′55.96″ W, 21°05′10.62″ N, 900 m	San Pedro Lagunillas, SOUTH
La Curva; Sugarcane	817	104°50′18.82″ W, 21°21′31.15″ N, 923 m	Xalisco, CENTRAL
Los Aguajes; Maize, Peach	1173	104°21′13.11″ W, 21°06′30″ N, 1901 m	Jala, SOUTH
El Llano; Mango, Jackfruit	1259	105°10′40.83″ W, 21°25′07.9″ N, 42 m	San Blas, NORTH COAST
Mesa del Nayar; Trading in produce	2979	104°39′11.86″W, 22°12′53.65″ N, 1383 m	Del Nayar, SIERRA - MOUNATAIN

(North coast), Tequilita (South), La Curva (Central), El Llano (North coast), Los Aguajes (South), and Mesa del Nayar (Sierra). Supplementary Information – 1 gives location map on each of these communities. Table 3 provides a brief summary of the data in ascending order of the number of the inhabitants.

Fig. 3 shows the availability and variability of solar energy for the sites chosen for this study obtained using PVGIS. Mesa del Nayar, in the Sierra region, located at 1383 m above the mean sea level (amsl) has an annual daily average insolation (I) of 6.4 kWh/m^2, which is the highest value. It also carries the lowest standard deviation (σ) of 0.78 kWh/m^2 with a variability (v) of 24%. Tecuitata located on the North coast at 219 m (amsl), with I of 5.64 kWh/m^2 has the lowest value and a relatively high σ, 0.95 kWh/m^2 with v of 34%. Despite the effects of such variability, all sites in this study exceed the national average value of I of 5.5 kWh/m^2-day. A slight difference of 12% is observed between the highest and lowest value of solar energy availability. In summary, Nayarit has a fertile soil, and is rich in solar resource.

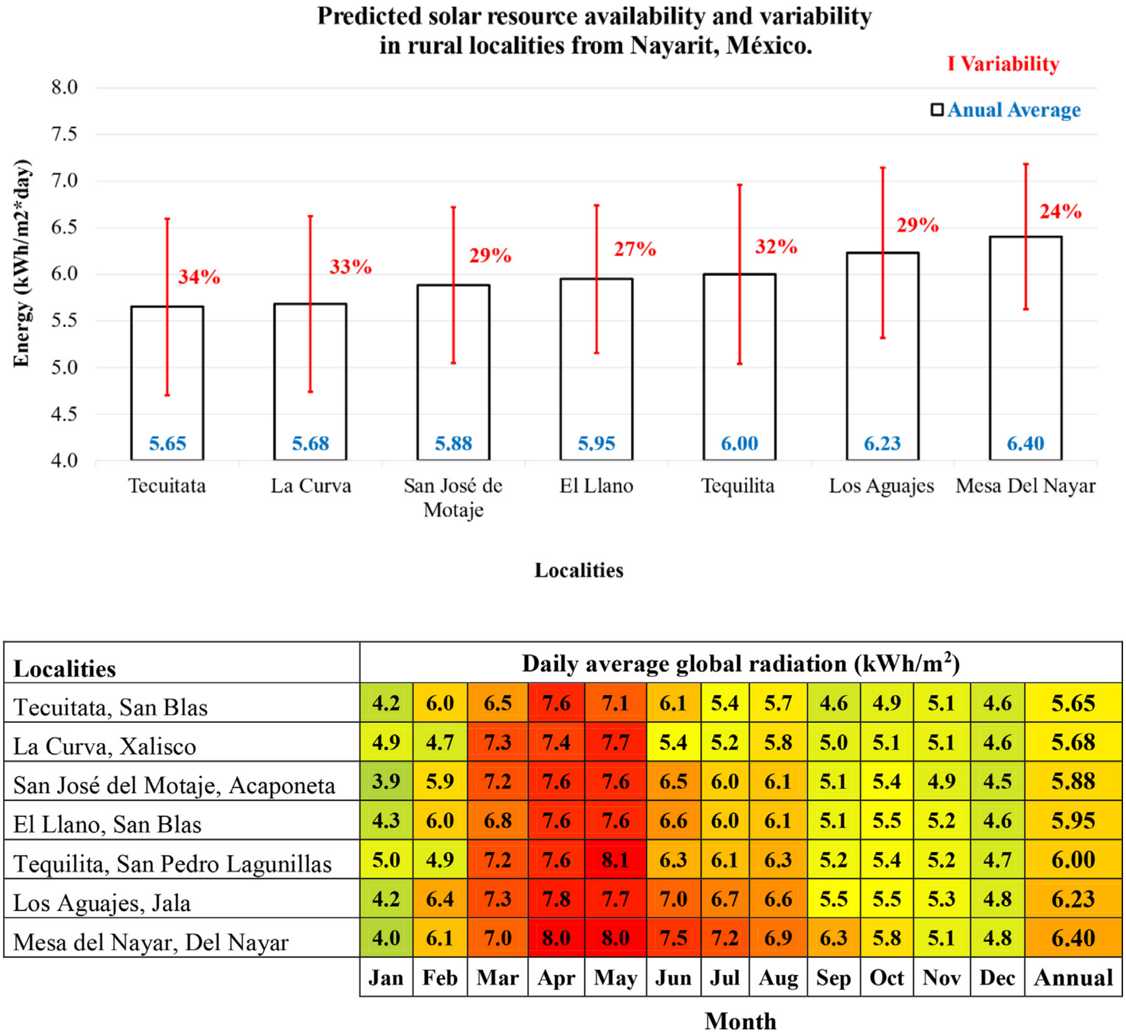
PVGIS also helps to estimate the PV performance in a specific location and for a specific PV technology (Psiloglou et al., 2020; Haffaf et al., 2021). For this sustainability study for Nayarit-Mexico, we compared the simulated performance obtained from PVGIS for the sites with the actual performance of a PV installation at the state capital of Nayarit, Tepic (Messina et al., 2014). We obtained data for the daily electric generation from a 2.4 kWp grid-connected roof-top PV system installed at the University of Nayarit, Tepic (Fig. 4). The daily operation data was obtained from the web-based DC-AC inverter database used in this grid-connected system for the period of 9 years from 2012 to 2020. The array consists of 10 modules Kyocera KD240GX-LFB - (240 W$_p$) of polycrystalline silicon cells rated at 15.0% module efficiency under standard test conditions. This installation covers a roof area 16.45 sq. m. The inverter used here is a Sunny Boy 3000US two-phase (120 V, 60 Hz each) system with maximum power rated to 3.2 kW. The inverter output data are recorded by a Sunny Web Box Data Acquisition System, which permits statistical analysis of daily and monthly data from the Sunny Portal website, as reported by us previously (Messina et al., 2014). Fig. 4 shows the System inclination angle at 22° to the horizontal and azimuth angle of 9° toward the southwest.

Fig. 5 shows the average kWh/kWp electric energy output per kWp-PV installed, for the months for the years 2012–2020:

a) Shown in black bar are the values predicted for any year by PVGIS for the 2.4 kW$_p$ system installed with orientation as illustrated in Fig. 4.
b) Shown in blue bars are the values for any year for ideal orientation for the same system – facing south with inclination suggested for the site by the PVGIS simulation software; and
c) In white bars are given the values obtained for each month during the period, as reported by the data-logger system.

Through these results, we establish that PVGIS is an easy, fast, and reliable free-access software tool for simulation of solar resource and PV performance, as has also been reported by other authors (Psiloglou et al., 2020; Haffaf et al., 2021; Psomopoulos et al., 2015). Differences exist between the predicted - black and blue bars and recorded (white bar) values during the months of November to May of the year, when the dust settling on the modules reduces the solar radiation received by the solar cells. During the months of June to October of the year the modules are constantly cleaned by the rainfall; and the predicted and recorded values of nearly 4 kWh/kW$_p$ are in close agreement. March–May months are indeed the months of high solar resources, as predicted and observed for the capital city Tepic-Nayarit, in agreement with data for the farming localities spread across the state, Table 3, Fig. 3(b).

The benefit of a grid-connected PV system for solar powered farm produce drying is that excess electric energy is injected into the grid at nearly 5 kWh/kW$_p$ during the months of March and April when the summer harvest has not yet set in. This energy is drawn back during the harvest months of June–August, when the solar radiation is impeded by cloud cover from the seasonal rain and also rain and cloud cover generated in Nayarit by the Pacific hurricane season. One may propose



Localities	Daily average global radiation (kWh/m^2)												
Tecuitata, San Blas	4.2	6.0	6.5	7.6	7.1	6.1	5.4	5.7	4.6	4.9	5.1	4.6	5.65
La Curva, Xalisco	4.9	4.7	7.3	7.4	7.7	5.4	5.2	5.8	5.0	5.1	5.1	4.6	5.68
San José del Motaje, Acaponeta	3.9	5.9	7.2	7.6	7.6	6.5	6.0	6.1	5.1	5.4	4.9	4.5	5.88
El Llano, San Blas	4.3	6.0	6.8	7.6	7.6	6.6	6.0	6.1	5.1	5.5	5.2	4.6	5.95
Tequilita, San Pedro Lagunillas	5.0	4.9	7.2	7.6	8.1	6.3	6.1	6.3	5.2	5.4	5.2	4.7	6.00
Los Aguajes, Jala	4.2	6.4	7.3	7.8	7.7	7.0	6.7	6.6	5.5	5.5	5.3	4.8	6.23
Mesa del Nayar, Del Nayar	4.0	6.1	7.0	8.0	8.0	7.5	7.2	6.9	6.3	5.8	5.1	4.8	6.40
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual

Month

Fig. 3. *Top chart*: Predicted yearly solar resource availability and its variation in the localities chosen for this study, placed in ascending order of the values obtained using PVGIS. The standard deviation of the data for a year is marked by the line in each case. *Bottom chart*: Maximum monthly average for the solar resource occurs in the spring months of March to May, when many tropical fruits mature for harvest, but much variations set in during June and July, during which the harvest season continues, but the solar resource varies due to cloud cover.

Table 4

Outlook and parameters for 25% of Nayarit's annual harvest of major fruit produce set apart for solar powered drying. Column 2 shows in kg, 25% of the annual production listed in Table 1, which for mango is 0.25 × 316,747,000 kg = 79,186,750 kg. To obtain the values in Column 3 for daily production, we assume that the harvest is evenly distributed over a three month period (90 days) for the crop, which for mango implies 879, 900 kg. For each fruit crop, the fraction of mass constituting seeds, kernels, shells or peels differs, which is excluded from the mass of the pulp to be dried. In the case of mango, a fraction 0.75 of the fruit is the pulp, which is 659,900 kg daily for solar drying, shown in Column 4. The pulp carries a major fraction of its mass as water, which is 0.83 for mango, hence amounting to 547,700 kg of water to evaporate daily in the dryers to produce 112,200 kg of dehydrated mango slices every day during the harvest season, Daily Dried produce (kg) = Column 4 – Column 6. The latent heat of vaporization of water of 2.26 MJ (0.628 kWh) per kg-water, places the drying energy requirement at 343,800 kWh daily for the mango slice drying, given in Column 7.

Crop	Volume production for drying (kg)	Quarterly production daily Avg. (kg)	Pulp (kg)	Water content (fraction)	Water to evaporate (kg)	Daily Energy need (kWh)
Soursop	3854,250	42,800	32,100	0.8	25,700	16,200
Jackfruit	5812,750	64,600	48,400	0.73	35,400	22,300
Mango	**79,186,750**	**879,900**	**659,900**	**0.83**	**547,700**	**343,800**
Watermelon	12,986,000	144,300	108,200	0.92	99,600	62,700
Pineapple	8563,000	95,100	71,300	0.87	62,100	39,100
Coconut	2651,250	29,400	22,100	0.72	15,900	10,000
Banana	8488,000	94,300	70,700	0.74	52,300	33,000
						530,000

Fig. 4. A 2.4 kW$_p$ PV system installed at the roof top of a building of the University of Nayarit, Mexico, installed in the year 2012. The daily production was monitored through an inverter-web-box over 9 years toward 2020.

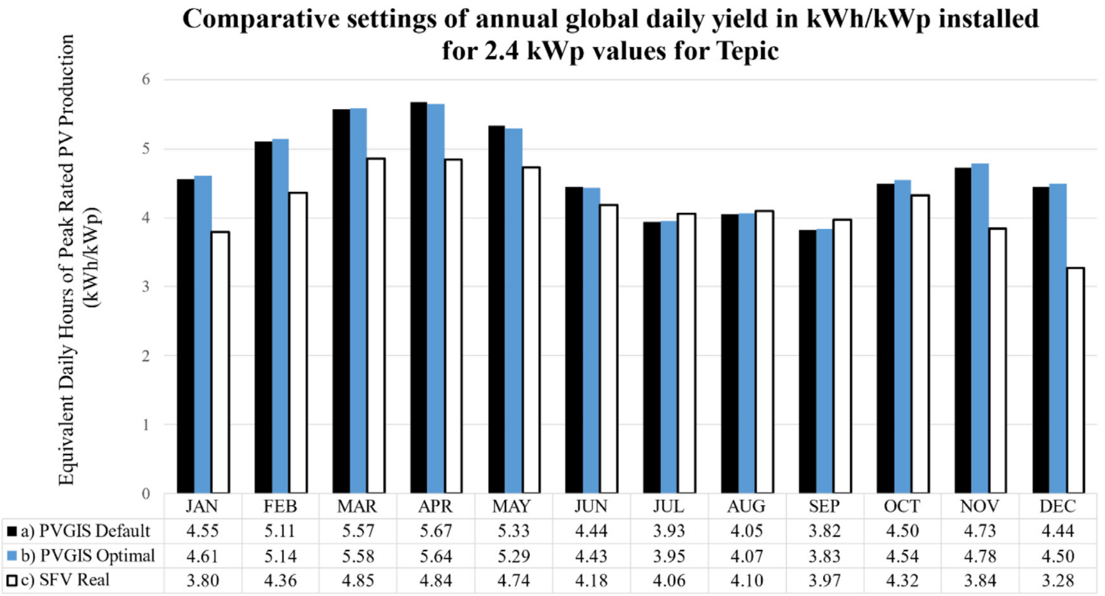
to increase the energy production during the dry months by cleaning the PV modules by pressurized water, but the sustainability and the overall benefit of the approach would depend on the specific site.

In solar drying projects of agricultural produce, a solar PV system would be necessary to provide energy to electric extractors to remove humidity from the solar drying chambers and to supplement the energy for electric heaters when the solar energy is impeded by cloud cover. The PV system may also help to preheat the drying system during the morning hours. These aspects are discussed in the following section (5.4). We assume a grid-connected PV system with net zero or negative energy use from the grid would help certify the drying as a “net-zero emission” processing. This would qualify such dried produce for reduced taxes and favored export/import duties. We consider that a certification to that effect will also qualify the product for a place in the organic/energy-zero racks with the distributors and for a preferential place in e-marketing and delivery networks.

5.4. Solar dryer energetics

Drying of farm produce using solar energy is relevant because in most tropical regions, the solar radiation resource is of 4–7 kWh/m^2/day in harvest seasons, similar to those seen in Fig. 3 for Nayarit locations. Drying of agricultural produce should be done at temperatures of 45–55 °C. Excessive temperature in fast-dried produce would result in a hardened crust, which may trap moisture in the interior and reduce the shelf life and/or cause produce browning of the dried product (Resnik and Chirife, 1979). Because of the low differential temperature (20–40 °C) with respect to the ambient temperature prevailing in the solar drying system, a high system efficiency (70%) is achieved in it with minimized thermal losses. We propose in Table 4 a scenario on the energetics of produce-drying where nearly 25% of the farm produces in Table 1 in Nayarit are set apart for *on-site* drying. In the energetics of drying we consider only the latent heat of vaporization of water. To produce 1 kg of dried product, the water content of nearly 4 kg should evaporate from 5 kg of a fresh produce (slices or pulp) at an energy input of 2.26 MJ/kg-water. This amounts to nearly 9 MJ for the 4 kg of water to evaporate. An electric dryer system efficiency of 70% entails: (9 MJ/0.7) x (3.6 kWh/MJ) = 3.57 kWh of electricity used up in the production of 1 kg of the dried produce. For the energy mix in the electricity supply, this means 1.25 kg of CO$_2$ equivalent emitted to the ambient for each kg of the dehydrated produce. The dehydration considered here represents the reduction of mass of the produce to 20% of the fresh produce, but the water content to be removed for specific produce differs, Column 5, Table 4.

At a system efficiency of 70% in solar drying, the average solar resource per sq. meter in Nayarit converted to thermal energy for the drying process from Fig. 3(b) is 4.2 kWh during the summer peak harvest season, April–July. For 659,900 kg of mango slices (pulp) set



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
■ a) PVGIS Default	4.55	5.11	5.57	5.67	5.33	4.44	3.93	4.05	3.82	4.50	4.73	4.44
🟦 b) PVGIS Optimal	4.61	5.14	5.58	5.64	5.29	4.43	3.95	4.07	3.83	4.54	4.78	4.50
□ c) SFV Real	3.80	4.36	4.85	4.84	4.74	4.18	4.06	4.10	3.97	4.32	3.84	3.28

Fig. 5. a) Shown in black bar graph is PVGIS daily global yield for the months JAN – DEC, in kWh/kWp-installed, evaluated for Tepic for the actual coordinates (Fig. 4) with inclination from the horizontal and azimuthal angle to southwest for the installed 2.4 kWp PV system; b) in blue bar graph is the value predicted for a PV installation with the optimum orientation and inclination parameters for the site suggested by the PVGIS software illustrating that the differences between a) and b) are small. c) Measured values from the system for the nine-year period 2012–2020 showing a notable reduction in the output for the summer harvest months of June to Sept, but with a good agreement between predicted and recorded values. The modules are maintained clean by the rainfall during this period, but the cloud cover from rainy season and hurricanes reduce the energy output. During the dry months of November to April of the year, differences are significant in the energy output: in December, 4.5 kWh/kW$_p$ predicted and 3.3 kWh/kWp recorded (reduction by 27%), assigned to dust settling on the glass cover of the PV modules, which results in diffuse reflection loss of the solar radiation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

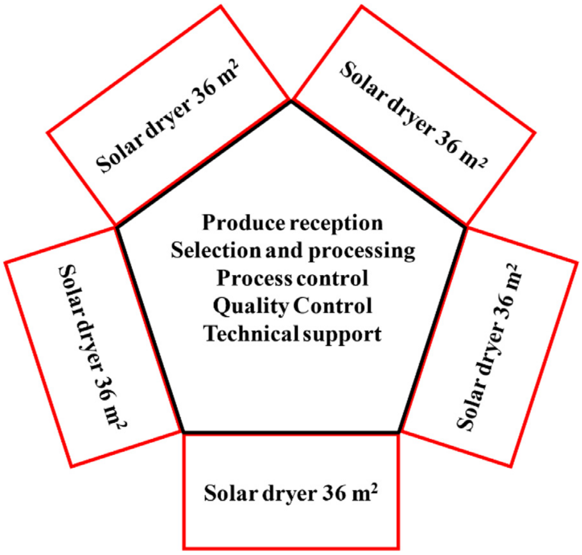


Fig. 6. Solar dryers arranged in clusters of five units to improve efficacy of operation. In this case, the produce reception, selection and processing of the produce is done in the central unit, and so is the quality control. The technical support team monitors the temperature and humidity of the drying ambient and of the produce and of the final dehydrated product as required for the desired shelf life. The maintenance of the PV-integrated grid system, which draws back electrical energy to activate auxiliary electric heater during cloud cover or night time operations are done using microcontrollers. Each dryer on clear days produces 40 kg dried slices, but the grid connected PV-system may help to increase the production by a factor of three to four.

apart for drying daily (Column 4), with water content of 547,700 kg (Column 6), and daily energy requirement of 343,800 kWh (Column 7), the dryer area requirement is 81,900 m^2. For drying other produce (Column 1–3) as well, the daily energy required is 530 MWh (1000 kWh = 1 MWh). Such an energy demand requires a collection area of: (530,000 kWh)/(4.2 kWh/m^2) = 126,200 m^2. This task is met in Nayarit farm locations by 3500 solar dryers, each with a collection area of nearly 36 m^2. Here, 36 m^2 is the approximate area provided under a canopy of 12 cover/roofing sheets of selected materials, available in standard sizes of 1.22 m (4 feet) × 2.44 m (8 feet).

The solar dehydrated food products from the 3500 solar powered dryers is approximately 175,000 kg (175 tons) per day. Each dryer with an aperture of 36 m^2 provides 150 kWh thermal energy daily for evaporating 220 kg of water contained in 260 kg of pulp or slices. In the case of mango, the slices come from 350 kg of the whole fruit from which 90 kg is separated as peel and seed. Daily production of dried slices is 40 kg. We shall present in Section 6, the feasibility of grid-connected PV powered solar dryers to increase the production three or four times this quantity.

Fig. 6 shows that these dryers may be arranged in clusters of three to six units with a centralized facility to provide quality control and technical support to achieve efficacy in operation. A cluster of five dryers shown here has an estimated daily production of 200 kg dried produce, which in the case of mango is processed from 1750 kg of the fruit.

5.5. Toward a near-zero emission, near-zero waste solar powered farm produce drying for sustainable socioeconomic development

Fig. 7 illustrates the process flow in each of the solar powered dryer described in Fig. 6, which has the potential to create jobs requiring different levels of technical skills created for the purpose or already available in the farming regions. For most of the process steps, the International Organization for Standardization (Switzerland) has set rules and standards on how raw materials are sourced, products are made, and quality control implemented, with all of these achieved in an acceptable work environment. A 2003 article examines the specific case of ISO14001 relating to sustainable development (MacDonald, 2005). Illustration in Fig. 7 refers to the specific case of mango (350 kg) entering a solar powered dryer, producing 40 kg of dehydrated mango slices in a drying run with three main process steps:

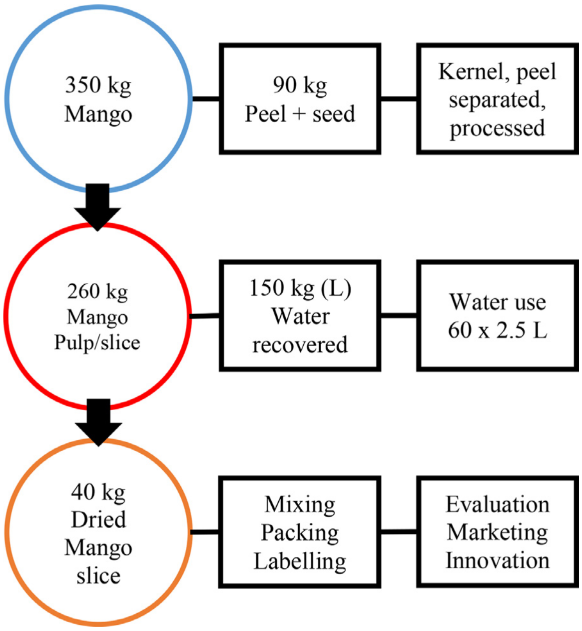


Fig. 7. Illustration of the process flow in a single drying run of mango in a solar powered farm produce dryer discussed further in Section 6.

(i) Reception, selection and processing: Each produce (350 kg whole fruit per drying run) is selected based on pre-established ripening level to produce the desired dried product so that the texture, taste and color are maintained. Mango slices (260 kg) arranged on drying bins enter the dryer. Peel and kernel (90 kg) are separated for further processing. Many studies suggest health benefits, which may be derived by adding ground mango kernel to grain flour in bread-making (Amin et al., 2018; Yatnatti et al., 2014; Kaur and Brar, 2017). The peel and kernel also serve as feed for freshwater fish or for langoustines in a zero-waste approach. In jackfruit processing, similar benefits exist from jackfruit seeds (Akter and Haque, 2018).

(ii) The solar powered dryer to be discussed further in Section 6 uses UV-Blue filtered solar radiation, which was found to inhibit darkening in the dried produce (Nair et al., 2020). Any fall in the dryer temperature due to cloud cover is compensated through auxiliary electric heating elements powered by grid-connected PV system of appropriate rating, which ensures that the drying process set at 45–55 °C is maintained. This helps meet with an established production schedule and with the bench-mark quality of the product. Solar PV powered extractors aid the transport of water vapor from the slices (260 kg) in the drying bin to a condenser, helping to recover nearly 150 kg (L) of water, which may serve as drinking water. In a single drying run nearly 40 kg of dehydrated slices are produced during 180 min, if the freshly cut slices are of 2.5 mm in thickness (Nair et al., 2020). Thicker slices require much longer drying time because water in the interior requires a diffusion process to migrate to the surface, which is slow to occur at such drying temperatures. The grid-connected PV systems and auxiliary electric heaters also permit pre-heating of the dryers in the morning or for extending the drying runs into the night by drawing back the energy from the electric grid, which was injected into it on brighter days. This permits more drying runs in a 24 h period, but still meeting zero-emission processing.

(iii) While each of the dried produce may have commercial prospects, mixed dried produce suitable for hydration to give nutritional supplement as illustrated in Fig. 2c) requires evaluation of nutritional values of the produce, shown in Table 2. Acceptable packing-type and labeling any ISO certification and of "zero-emission" and "zero-waste" production would attract consumer attention. However, this requires continuous monitoring and quality control to maintain the certification. Further, the 2 + 3 or 3 + 2 daily servings of fruits or vegetables discussed in (Ashfield-Watt et al., 2004), does not stop innovative ideas of introducing servings of a mix of dried fruits and vegetables benefitting from their combined nutritional contents, dietary fibers (Siriwattananon, 2016) and antioxidants (Shetty et al., 2013) to build and maintain a healthy body.

The process flow discussed here implies the creation of jobs requiring personnel from different disciplines at the farming locations. The solar powered drying of the farm produce at the site brings-in technologies and results of recent research on energy and environment, food and nutrition and their relevance to a healthy living in the rural farming communities. Through this, the rural region becomes nationally relevant and takes a central stage in the sustainable development of a country and the world.

5.6. Prevailing perception of renewable technology integration in farm production and processing and the need to recognize a transdisciplinary approach

With a vast farm production of tropical fruits, presently at 500,000 tons annually, and with the abundance of solar energy of more than 5.65 kWh/m^2 of daily average for the whole state of Nayarit - Mexico, as predicted by PVGIS, solar powered drying of the produce at the farm-site may establish as a road for its sustainable development. We proposed above how drying of up to 150,000 tons of tropical fruit in Nayarit, giving 30,000 tons of dehydrated produce per harvest season, may be done in small dryer units, creating jobs and rural prosperity. The sustainability features of the approach presented here have also the potential to be acceptable with suitable adaptation in many rural settings in the world.

The survey for "Energy and Alimentation Diagnostics in Rural Communities in Nayarit" was conducted during the months July to September 2021 by university students belonging to the seven communities listed in Table 3, accompanied by some of the co-authors of this work. The survey was based on a semi-structured format with 11 major sections and 62 subsections (Supplementary Information – 1, pages 23–24, in Spanish) to fill-in a response including the disdain the communities hold about such academic exercises often with no benefit to themselves. The Sections examined. Background information (3 sub sections); 2. Personal data (7); 3. Employment data (8); 4. Housing characteristics (2); 5. Social security (6); 6. Food procurement and eating habits (9); 7. Energy use pattern (4); 8. Agricultural farm production (11); 9. Commercialization of the produce (7); 10 Residue management (3); and 11. Social participation (2). The analysis of this survey was done for each locality, and was also done to give a general pattern to reveal opportunity for solar powered drying of the farm produce to open a path toward sustainable rural development.

We realized from our close interaction with the community while carrying out the survey that there exist challenges in implementing this approach. Through interviews conducted by university students (UAN 2021) with parental and social connections with the residents in the farming communities many outstanding feelings and perceptions on the academic and governmental interventions in farm life have been identified as obstacles. Such feelings expressed to a member within the same community testify to their veracity:

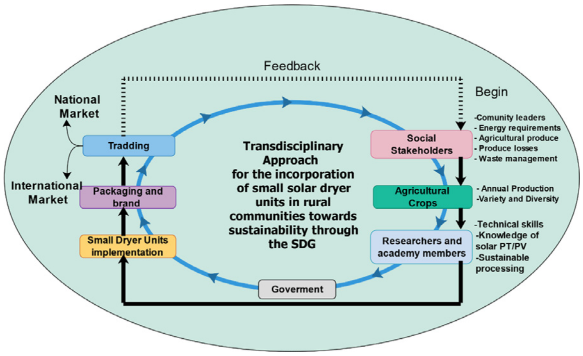


Fig. 8. Epistemic system scheme for the transdisciplinary approach to achieve the goals presented in this work.

> "We are afraid to associate with new technologies because we always lose out."

> "You have always taken advantage of us."

> "We have many doubts as to how to organize ourselves to meet with what the government institutions impose."

> "When we achieve organizing ourselves that way, the institutions change their rules and impose the changed rules."

> "We cannot meet with such policy changes; we no longer believe in what you bring to discuss."

> "We better work alone as we always did."

Thus, transdisciplinary work is essential to build up confidence for the rural and traditional farming communities to venture into solar photothermal/photovoltaic dryers for the sustainable processing of farm produce at the farm site. Feasibility of the approach outlined above (5.5), which may be obvious from an academic outlook, may not hold relevance at the community level.

Fig. 8 shows the epistemic system scheme for the transdisciplinary approach required for such communal acceptance, resulting in a success. The systemic sphere is embedded in the environment. Here, the participants are structured. They develop different cognitive levels of understanding the underlying problems and developing the prospects. The academy serves to coordinate dis-aggregated knowledge in different scientific disciplines such as energy, agroecology, social sciences, engineering, technology and nutrition and propose methodologies to integrate these through interdisciplinary work. The penta-helix alliance incorporates researchers and academy members, government institutions, producers and entrepreneurs, rural communities and the environment. In this way, the complexity of the problem is reduced, as the integration of the participants into the common problem enhances. This is a holistic approach to study rural development problems. It brings together academic and general population with a common interest in applying their knowledge to build familiarity with a location and help generate social benefits.

The synergies among academy, social participants, producers, entrepreneurs, and government are slowly built, but these are built to last. In the present case, the rural community is the supplier of agricultural products and materials used in the solar dehydration processes. The academy members are the link between the producers and the state government. The Penta-helix alliances ensure the success of the projects and their multiplier effects. Through this approach we hope to build up confidence to venture into solar photothermal/photovoltaic solar dryers for a sustainable processing of farm produce for rural development.

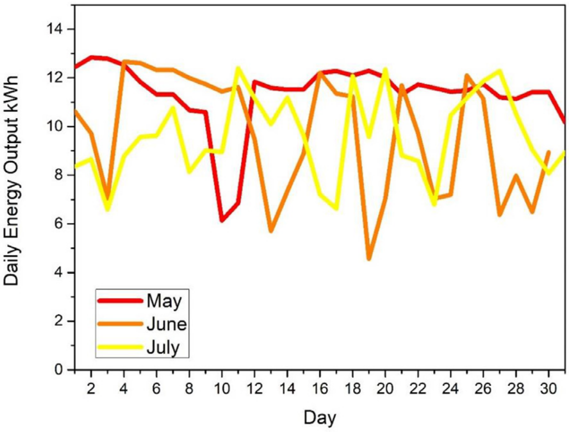


Fig. 9. Daily fluctuations in the energy production from a 2.4 kW_p PV system installed in Tepic, Nayarit during the months of May, June and July 2021 due to cloudy skies caused by the hurricane – rainy days. The peak harvest season for some of the tropical fruits also occurs in the same period, thereby making the grid-connected PV integrated solar dryer system a necessity for "zero emission" produce drying.

6. Strategy for the integration of solar energy technologies into farm production and produce processing

The data presented in Fig. 3 on the solar resource availability in the Nayarit state is generally supportive toward the integration of solar energy technologies on a large-scale in: (i) agricultural farm production and (ii) farm produce processing initiatives to help meet the "zero emission" targets in both. However during the months of May to July, there is a decline in the solar resource due to the setting-in of the hurricane season initiated in the Pacific Ocean.

Fig. 9 illustrates the daily fluctuations in the energy production from the 2.4 kW_p PV system in Tepic, Nayarit for the months of May, June and July of the year 2021. The unpredictability of solar resource from one day to the next is evident during these months. During 10 days in the month of June 2021, the production dropped below 7 kWh/day, from a peak of 12.7 kWh/day for the 4th of June (5.29 kWh/kW_p). The output was 4.6 kWh/day from the PV system (1.9 kWh/kW_p) on the 19th of June. Similar fluctuations occur during the months of May and July as well. When we take note that this happens during the peak harvest season of tropical fruits of soursop, jackfruit and mango, we find that grid connected photovoltaic installation is a necessary strategy for the produce processing to qualify for their "zero emission" certification. During more than two weeks cloudy skies may prevail, which when combined with a high humidity in the ambient aggravates bacterial and fungal activities on the ripe farm produce.

We consider that solar PV systems interconnected to the national grid is an ideal means to overcome this limitation. Under the existing electric energy regulation for grid-connected small-scale photovoltaic systems, the energy can be uploaded during the entire year and drawn from it as needed during the year and obtain a "net-zero" grid electricity user status.

Fig. 10 shows a schematic for a multilevel solar dryer with a grid-connected PV system integrated into it to meet this perspective. The features of this solar dryer include the following:

(i) This is a duplex dryer system, Fig. 10a), with a central passage for loading and unloading the sliced produce or pulp, which is spread on drying bins at a thickness of 2.5 cm, as suggested in a previous paper (Nair et al., 2020).

(ii) The roofing of the structure is of cellular polycarbonate sheets of 6 or 8 mm wide cells, typically of 122 cm x 244 cm (4 ft x 8 ft), weighing 1 kg/m^2. These carry a copper chalcogenide semiconductor thin film coating of 120 nm in thickness applied inside the cells (Fig. 10b) using large-area batch production by chemical deposition technique, as described in Nair et al. (2020). Use of six sheets on either side of the duplex system creates an aperture of nearly 36 m^2 for the entry of UV filtered solar radiation at midday. In a Nayarit location the radiant power entering the inside of the dryer is nearly 860 W/m^2 (0.86 kW/m^2). Thus, this facility is a 30 kW solar dryer system. The UV filtering by the semiconductor coating nearly eliminates the UV content of the solar radiation and thus helps inhibit the browning of certain produce in the dehydration process, and thereby improves its consumer appeal. On a bright day with 5.6 h equivalent of 1 kW/m^2 of solar radiation at the site, the thermal energy available is 160 kWh, which at a 70% drying system efficiency provides 110 kWh per day of energy. This goes toward evaporating the water content in the sliced produce. As discussed in Section 5.4, this amounts to 175 kg of water, which meets 80% of the requirement to evaporate 220 kg of water contained in 260 kg of mango slices (pulp) illustrated in Fig. 7. We expect some heat recovery from the condenser system, in which the water vapor from the drying produce condenses, releasing 2.26 MJ of energy per kg of condensed water. Further, the PV powered electric extractors compensate for any energy shortfall for the drying process. As discussed in Section 5.3, meeting the task of drying 25% of the tropical fruit produce in Nayarit calls for 3500 of these dryers. They are arranged in clusters for efficacy of operation, as illustrated in Fig. 6. The dryer systems carry auxiliary electric heating elements. They draw energy from the grid during the night time or in the morning or evening enabling to complete three to four drying runs during a 24 h period in the summer harvest season.

(iii) The PV system integrated to the dryer continuously injects the electric energy to the grid during daytime; it powers the extractors located at the bottom of the dryer drawing the heated air from the top of the dryer flowing through the bins. The humidity-laden air is dehydrated in the condenser system, and the warm air joins the heated air at the top part of the dryer system. The production of nearly 150 kg (litres) of water per 40 kg dried produce represents a sustainable recovery process for water. Auxiliary electric heaters integrated in the dryer system meet its drying needs under cloud cover. The PV system capacity is designed for each site. According to the 2020 PV Roadmap (Wilson et al., 2020), the module sale price on an average has dipped toward \$0.20 US per W_p for silicon solar cells by the year 2020. This is a ten-fold reduction in the cost for PV modules of US\$2.00/W_p from the year 2010. Any reduction in the efficiency of the PV modules is not more than 0.5% per year of the installed capacity, which implies that the installed PV capacity of 30 kW_p today (2022) would remain close to 25 kW_p by the year 2051. Thus, grid-connected PV system integrated to a solar dryer for drying of the farm produce suggested here appears economically viable. This has not been the case in an immediate past.

The solar powered dryer with a PV system interconnected to the electric grid discussed here carries many innovative features:

(a) The reduction in the cost of the PV modules by the year 2022 and the prevailing norms in many countries permit interconnection of the system to the electric grid through an approved class of inverter. The grid electricity eliminates the lack of dependability of the temperature or the duration of the drying process, which has limitted the acceptability of conventional solar dryer systems in the farm sites (Lingayat et al., 2021).

(b) The integration of the UV-filter semiconductor coatings of thickness of 100 nm in cellular policarbonate for solar drying of farm produce is an innovation, first reported in 2020 (Nair et al., 2020). These coatings were originally developed in the 1990′s for window glazings in built-environment to achieve UV filtering, comfort and energy efficiency. These are copper sulfide

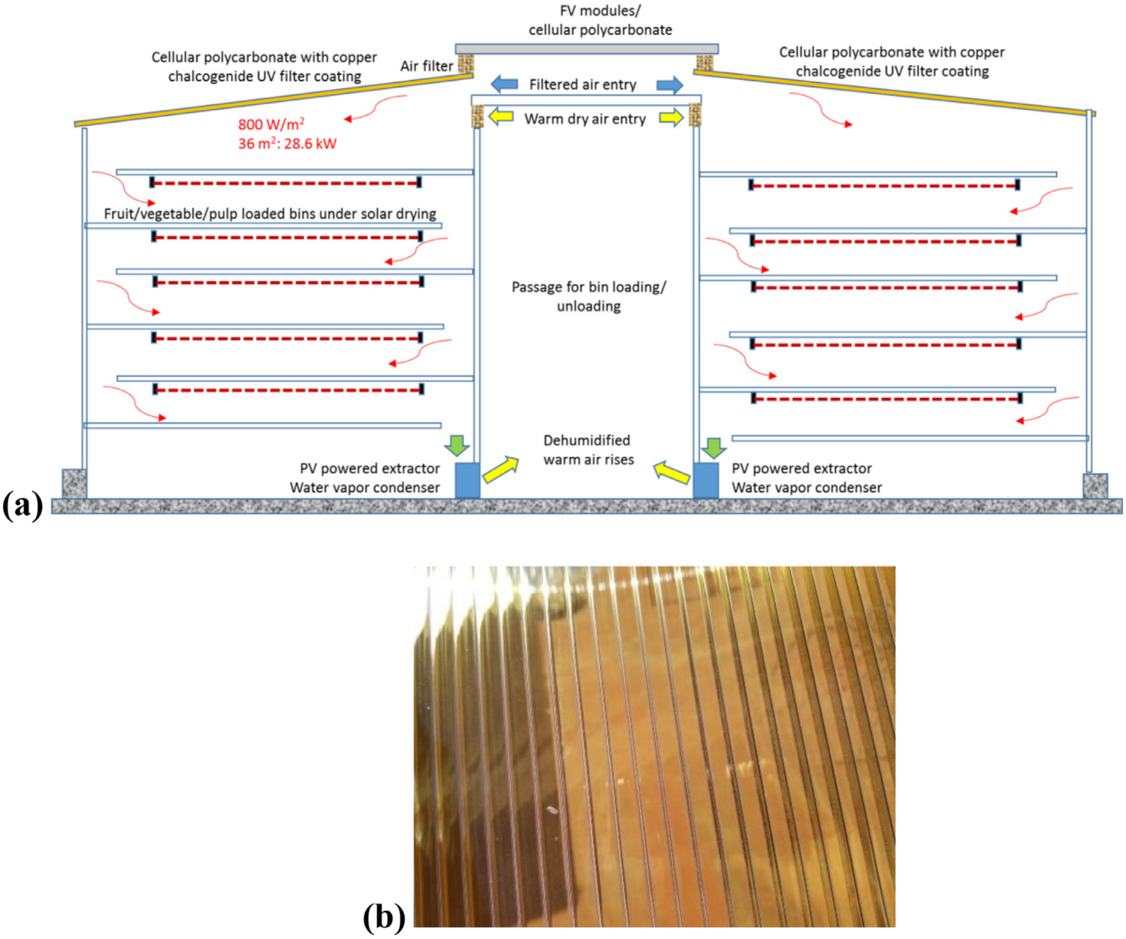


Fig. 10. (a) Schematics for a solar powered dryer for farm produce, which integrates UV filtered solar radiation to provide thermal power for drying, by drawing filtered air heated by photothermal power produced by absorbed solar energy at the polycarbonate cellular sheets carrying copper chalcogenide thin film (120 nm) coatings inside the cells. PV powered extractor/condenser system located at the bottom returns dehydrated warm air back to the drying bins after collecting the water content from the farm produce undergoing drying. The PV system mounted at the top may be interconnected to the power grid, which can supply electric heating elements located in the dryer to compensate for reduced solar resource under cloudy skies or during morning and evenings or for night time drying. (b) Cellular polycarbonate sheet (122 cm × 244 cm) with the semiconductor coatings applied inside the cells, reported in ref (Nair et al., 2020). The coated cellular polycarbonate sheet reduces the ultraviolet A and B components of 46 W/m^2 in intensity in air mass 1.5 solar radiation to 0.2 W/m^2; violet and blue-green components from 139 to 8 W/m^2. Estimate for reflected solar radiation, 140 W/m^2; transmitted, 270 W/m^2; absorbed, 590 W/m^2.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Nair et al., 1991; Hu and Nair, 1996) and/or copper selenide coatings (García et al., 1999), prepared on glass or plastic substrates from dilute chemical solutions at room temperature. Large-area coating technology, and the optical and thermal characteristics of these coatings were discussed in (Nair et al., 2020). Because cellular polycarbonate may contain bisphenol A (BPA), which is known to be harmful to health (Bittner et al., 2014), we advocated the retention of the polyethylene foil covering on the sheets or the use of an adhesive food-safe poyethylene foil on the polycarbonate sheet to avoid any contact of water vapor condensing on it and dropping to the drying bins. This is an unlikely event, because the polycarbonate sheet is the hottest surface in the solar dryer. Water vapor from the drying roof condenses on cooler surfaces. However, if the dryer is used after the sunset using grid-electricity, food safety must be assured.

(c) Recovery of water from the drying produce, envisaged in the drying schematics in Figs. 7 and 10 is also a novelty. We estimated that each drying run may produce nearly 150 liters of water, from the condensing water vapor, which serves as drinking water. This is not a usual feature in solar dryers (Janjai et al., 2011; Lamidi et al., 2019; Belessiotis and Delyannis, 2011; Lingayat et al., 2021).

7. Perspective on the prospects of sustainable development through solar powered processing of agricultural farm produce

With Nayarit State – Mexico as a specific case study, we presented above how the benefit from scientific and technological development can be brought to the rural region for its sustainable development. Solar photovoltaic modules, encompassing the best of scientific knowledge and technological development, carry a 500-fold drop in price per watt-peak from US$100 (normalized to 2019 US$) in 1976 to US$ 0.2 in 2020 (Wilson et al., 2020). Solar photothermal collectors easily found their way into solar food drying systems in the 1980′s, but solar photovoltaic module was considered costly for such systems and was left out. Even when the PV module prices have dropped toward US$5 by the year 2000 and down to US$2 by the year 2010, its application did not permeate into solar drying systems. A notable innovation was the use of solar PV powered extractors reported in industrial-scale solar dryer systems for fruits and vegetables reported in 2010 (Janjai et al., 2011). However, their power rating was modest – nine direct current extractors powered by three 50 W_p modules (150 W_p) to expel humidity from a dryer area of 150 m^2. The ten-fold price drop in the subsequent ten years toward the year 2020 (Wilson et al., 2020) now permits the use of solar PV modules at 1–30 kW_p rating in the design of solar dryers, as shown in the schematic in Fig. 10a). Use of optical coatings in the polycarbonate sheets was not introduced previously. The 2.4 kW_p PV system seen in Fig. 4, with its characteristics monitored during the years 2012–2020 shown in Figs. 5 and 9 is an affordable grid-connected PV system to integrate into the solar dryer of Fig. 10a). A five unit cluster-dryer system seen in Fig. 6, capable of processing 1750 kg of fresh produce daily (200 kg dried produce) illustrated in Fig. 7, requires a 12 kW_p system. For a cluster, it is practical to have resident technical support personnel.

The benefit of plant based diet toward achieving a healthy living has gained much public awareness through United Nations (S. of I. Ministry of Health 2021) and many governmental programs (FAO. 2020). However, the rural regions from where the plant based diet is sourced, do not appear as partners. This is where financial benefits should reach.

In this work we mentioned mainly the tropical fruit crops and illustrated the discussion with mango from Nayarit State – México. Worldwide, mangoes (28%), bananas (29%) and citrus fruits (12%) represent those with major consumption (The countries of 2021). Estimate made by FAO for mango whole fruit production for the year 2021 places India, China and Thailand as top producers with 15, 4.3, and 2.6 million tons; followed by Indonesia, Pakistan and Mexico with nearly 2 million tons annually, and Brazil, Bangladesh, Nigeria and The Philippines with about 1 million annually. Thus, solar powered drying of this produce is applicable worldwide. Setting apart 25% of the farm produce to drying at the farm sites would help reduce the food loss and help meet the sustainable development goals globally. It would simultaneously help to improve the rural income and the gross domestic product of these regions. A “bumper harvest” in mango often creates a glut in its sales price (Times of India 2021) and a large fraction of the produce perishes before reaching the customer. It is unfortunate that along with the perished mango is also discarded its seed, which also holds high nutritional value and helps constitute functional food (Yatnatti et al., 2014; Kaur and Brar, 2017; Amin et al., 2018). The solar powered dryers at the farm site help alleviate this situation.

While most illustrations made here are on ripe mangoes, the use of raw (green) mangos, which may be dried as slices or as ground powder for culinary purposes is popular in Asian countries. This implies that the solar powered dryers come into use earlier in the year. Likewise, drying of tuber crops in slices or to be ground into flour allows the use of these dryers during many months of the year. Hence, these solar powered dryers hold the potential to become an essential asset to the rural farming communities, helping the nations to achieve sustainable development.

8. Conclusion

We suggested in this study that the introduction of agricultural farm produce processing in solar powered dryers may substantially reduce food loss at the farm site and food waste by the consumers. Both these help meet Sustainable Developmental Goal 12 on responsible production and Responsible consumption. With an increasing public awareness on the advantage of plant based food toward a healthy living, consumer preferences for minimum-processed food with zero-emission practices, and with a drastic reduction in price of solar PV modules, these dryers offer much perspectives for rural sustainable development. This scenario in 2022 did not emerge even in an immediate past.

Major conclusion of this study, based on our close contact with the rural communities, is that the overall success of solar powered dryers toward achieving such goal requires meeting with the following tasks and achieving them through a transdisciplinary holistic approach:

(i) Setting-up effective communication among academy-producer-industry partners.
(ii) Survey of the volume of the farm produce.
(iii) Solar resource availability by simulation programs and establishing the reliability.
(iv) Adequate design of the dryers and choice of their location to allow for grid connection and proximity to the farm locations.
(v) Implementation and adaptations of the process flow for each produce and logistics of produce acquisition in a near-zero CO_2 emission scheme.
(vi) Innovation in processing and packaging within a near zero-waste scheme.
(vii) Evaluation of nutritional quality of the product and adaptations.
(viii) Diversification of the range of products offered using consumer feedback.
(ix) Research and development at the academy on energy, water, land use sustainability, and
(x) Feedback from the academy to farming community and vice-versa.

We hope the present work would lead to further contributions from many other research groups.

Author credits

SM and PKN conceived this study and compiled major part of the manuscript. FG performed the PVGIS simulations for the locations and analysed the solar PV data. CS and HT participated in the overall activities, graphics, and coordinated the site interviews. CJ and GP compiled and analysed the produce data and nutrition information.

Research data policy and data availability statements

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request. Supplementary Information – 1 (40 pages) is part of the Phase-1 Report of the Project 315171, available in the original version, in Spanish.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors gratefully acknowledge the support of CONACYT- Mexico through the project FORDECYT 2020 grant 315171 and PRONACES 2022 grant 319456. We acknowledge the producers, entrepreneurs, social groups, and community members for sharing with us their knowledge. We are grateful to community leaders in the study communities for trusting us with disclosing their actual feelings in extended interviews.

Funding

This work was supported by Consejo Nacional de Ciencia y Tecnología CONACYT- Mexico through the project FORDECYT 2020 grant 315171 and PRONACES 2022 grant 319456.

Supplementary materials

Supplementary material associated with this article can be found in its original Spanish language text, in the online version, at doi:10.1016/j.clcb.2022.100027.

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