A COMPARATIVE ENVIRONMENTAL ASSESSMENT OF DIRECT, INDIRECT, AND MIXED-MODE SOLAR DRYERS

KÖZVETLEN, KÖZVETETT ÉS VEGYES ÜZEMŰ NAPENERGIÁS SZÁRÍTÓK ÖSSZEHASONLÍTÓ KÖRNYEZETI ÉRTÉKELÉSE

ABRAHAM KIPROP JUMA – ZOLTÁN KURJÁK – JANOS BEKE
juma.abraham.kiprop.2@phd.uni-mate.hu

Abstract

The present study offers a comparative environmental assessment of direct, indirect, and mixed-mode solar dryers to identify the most sustainable drying technology. Solar dryers are promising alternatives to open sun drying and fossil-fuel-powered dryers. They are also well-suited for rural areas in developing countries due to the widespread availability of solar energy. This analysis focuses on material sustainability, carbon footprint, and drying and energy efficiency. Direct solar dryers (DSDs) are simple to construct and can be made using locally available materials. However, they suffer from poor temperature control and low efficiency, which can negatively affect the quality of food products. Indirect solar dryers (ISDs) offer better performance than DSDs but involve additional components, making them more expensive to construct.

Mixed-mode solar dryers (MMSDs) have the shortest drying time and the highest drying efficiency. However, they also have the greatest environmental impact due to their complex structure and high material requirements.

There is a need to balance affordability, environmental impact, and performance in solar dryer designs to serve rural farmers in developing countries effectively. Future studies should focus on integrating localized and eco-friendly materials into solar dryer construction.

Keywords: *solar dryer, environmental impact, carbon footprint, material sustainability, embodied energy*
JEL Code: *L64, O13, Q42*

Összefoglalás

Tanulmányunk célja, hogy egy összehasonlító környezeti értékelés segítségével meghatározza a fenntarthatóság szempontjából legkedvezőbb szárítási technológiát, a közvetlen, a közvetett és a vegyes üzemmódú, napenergiát hasznosító szárítók közül. Ezek a szárítók ígéretes alternatívát jelentenek a napon történő természetes szárítás és a fosszilis tüzelőanyaggal működő szárítók helyettesítésére és kifejezetten jól használhatóak a fejlődő országok vidéki területein is a napenergia egyszerű elérhetősége miatt

Elemzésünk első sorban a használt anyagok fenntarthatóságára, a szén-dioxid-lábnyomra, valamint a szárítási- és energiahatékonyságra összpontosít. A közvetlen napenergiával működő szárítók (DSDs) egyszerűen felépíthetők, és helyben beszerezhető anyagokból is elkészíthetők, azonban a hőmérséklet-szabályozásuk nem megfelelő és alacsony a hatásfokuk, ami negatívan befolyásolhatja a szárított termék minőségét. Az indirekt szárítók (ISDs) jobb teljesítményt *nyújtanak, mint a közvetlen működésűek, de több részegységből állnak, ami költségesebbé teszi a megépítésüket.*

A vegyes üzemmódú szárítók (MMSDs) rendelkeznek a legrövidebb szárítási idővel és a legnagyobb szárítási hatékonysággal. Ugyanakkor az összetett szerkezetük és nagyobb anyagigényük miatt a környezeti hatásuk a legnagyobb.

A napenergiát felhasználó szárítók tervezésénél olyan egyensúlyt kell teremteni a megfizethetőség, a környezeti hatás és a teljesítmény között, hogy hatékonyan szolgálhassák a fejlődő országok vidéki gazdálkodóit. Emiatt a további tanulmányoknak arra kell összpontosítaniuk, hogy a helyben fellelhető és környezetbarát anyagokat hogyan lehet felhasználni a szárítók építése során.

Kulcsszavak: *napenergiás szárító, környezeti hatások, szén-dioxid-lábnyom, anyagok fenntarthatósága, beépített energia*

Introduction

Drying is the oldest method used for food preservation. It has undergone evolution since the ancient world. However, traditional drying methods remain dominant in rural areas, particularly in developing countries. TIWARI (2016) and WATSON et al. (2024) denote that rural farmers in developing countries rely on open sun drying to preserve their crops. However, the method has many challenges. Long drying hours, contamination, large drying areas, weather dependency, and rodent invasion are the key challenges associated with open sun drying (JANGDE et al., 2022). The shortcomings of open solar drying have resulted in innovations in the drying field. The growing human population has also increased pressure on food demand. KHALIL et al. (2023) estimate that the world population will continue rising, making the need for more food production a necessity. Despite the increasing demand for food, the available drying technologies are insufficient in preserving it. Post-harvest losses are as high as 40% in developing countries (BALASUADHAKAR, 2021). The growing human population and high food loss have led to the development of different drying technologies. Conventional dryers relying on fossil fuels have been employed to extend product shelf life. However, the adverse impacts of fossil fuels on the environment make these dryers untenable in the long run. Despite contributing significantly to greenhouse gas emissions, conventional dryers are inaccessible to rural farmers, as some are not connected to the national grid (LAMIDI et al., 2019). Recent focus has shifted to sustainable drying technologies.

Solar drying is at the center of sustainable drying. Solar dryers are an advancement of open sun drying, as they provide a controlled application of solar energy in the dehydration process. The field of solar drying has gained much interest in recent years due to the vast availability of solar energy and the shortcomings of dryers already in the market. Although there are different types of solar dryers, they can be categorized into broad categories depending on their design, heat transfer, airflow, and auxiliary energy source (FERNANDES and TAVARES, 2024). As the world embraces eco-friendly technologies, solar dryers are at the center of sustainable drying solutions due to the abundance of solar energy and the low carbon emissions associated with the technology.

This paper aims to perform an environmental assessment of the existing solar drying technologies. The focus will be to analyze material sustainability, compare carbon footprint, and drying and energy efficiencies of the dryers. A clear understanding of these technologies is vital in guiding innovations in the drying sector and aiding policymakers in investing in the right technologies that will not only enhance drying efficiency but also foster environmental sustainability.

Classification of Solar Dryers

KHALIL et al. (2023) provide a detailed classification of solar dryers. The researchers explain that the dryers fall into four broad categories, as shown in Figure 1. Direct, indirect, mixed-mode, and hybrid dryers operate on the same principle of blowing air through a drying chamber to remove moisture from the products. However, each technology has distinct features and varying economic and environmental impacts.

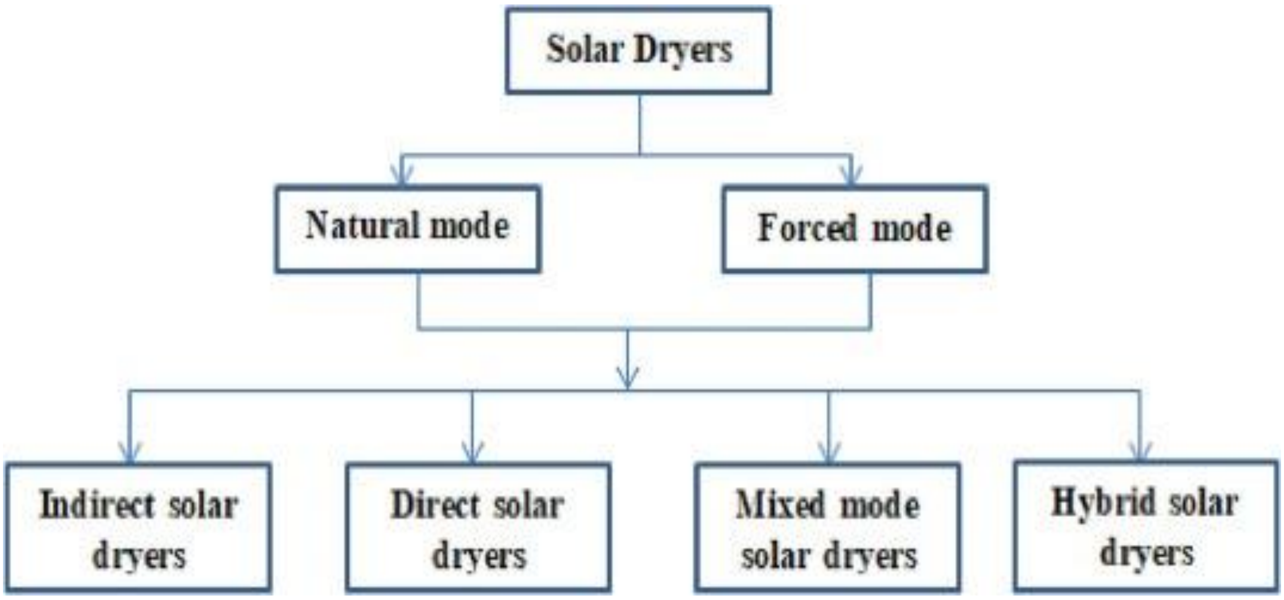

Figure 1. Classification of solar dryers
Source: KHALIL et al.(2023)

Direct solar dryers (DSDs)

In direct solar dryers (DSDs), solar energy is used to directly heat the products enclosed in a transparent drying chamber. Figure 2 shows the working principle of the dryer. Airflow can occur either through natural or forced convection. HIDALGO et al. (2021) investigated a direct dryer under both forced and natural air convection. The researchers found that dryers using forced convection have higher drying efficiency and lower specific heat consumption compared to those using natural convection. The ease of use and low construction cost make direct solar dryers suitable for rural setups (DEEPAK and BEHURA, 2023). However, the researchers highlight a major shortcoming of these dryers: the lack of control over drying temperatures. There are different types of direct solar dryers, such as greenhouse dryers, cabinet dryers, foldable dryers, tent dryers, tunnel dryers, and chimney-dependent cabinet dryers. All these dryers work on the same principles but vary in the design of the drying chamber and airflow mechanism.

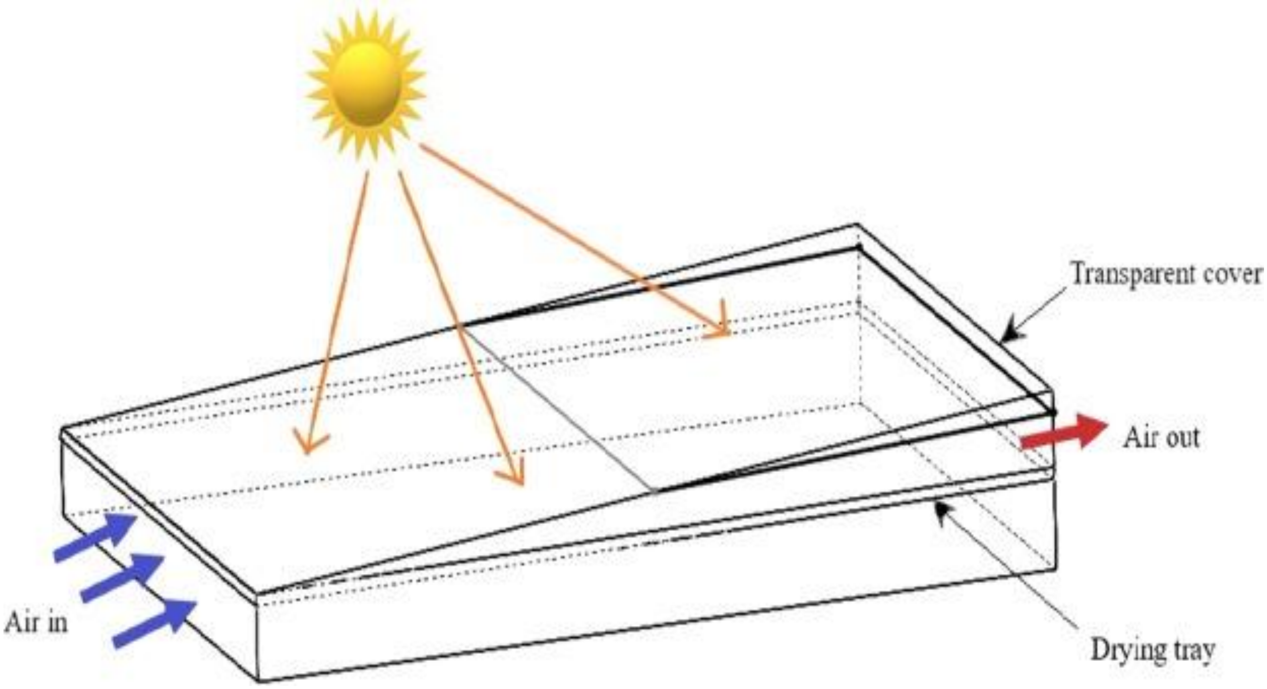

Figure 2. Schematic overview of a DSD
Source: KAMARULZAMAN et al. (2021)

Indirect Solar Dryers (ISDs)

Unlike the DSDs, indirect solar dryers (ISDs), (Figure 3.) dehydrate products without directly exposing them to solar radiation. Its working principle is based on a solar air heater. The heater preheats the drying air before it enters the drying section. The air heater captures solar energy and uses it to heat air. The dryers can also be operated in active or passive mode, as is the case with the direct solar dryers. DEEPAK and BEHURA (2023) denote that indirect solar dryers are suitable for products sensitive to UV rays, such as lemons. The researchers further depict indirect drying as superior to direct drying, as there is control of the drying temperatures and the dryer has a better moisture removal rate. However, indirect drying is costly due to the complexity of the system, which makes it unaffordable for small-scale farmers (DEEPAK and BEHURA, 2023). The other shortcoming of the dryer is its weather susceptibility, as no thermal energy is stored in the system. There are different types of indirect solar dryers based on air heaters, such as flat plate collectors, evacuated tube collectors, and parabolic trough collectors. The indirect solar dryers can also be integrated with chimneys to enhance drying efficiency.

The performance of indirect dryers can be enhanced by integrating thermal storage materials in the dryers. Studies have shown that drying efficiency increases while drying time decreases when indirect solar dryers are integrated with thermal storage materials. The key factor influencing the performance of the dryers is the type of thermal storage materials used. Thermal storage materials can be integrated not only into ISD but also into other dryers.

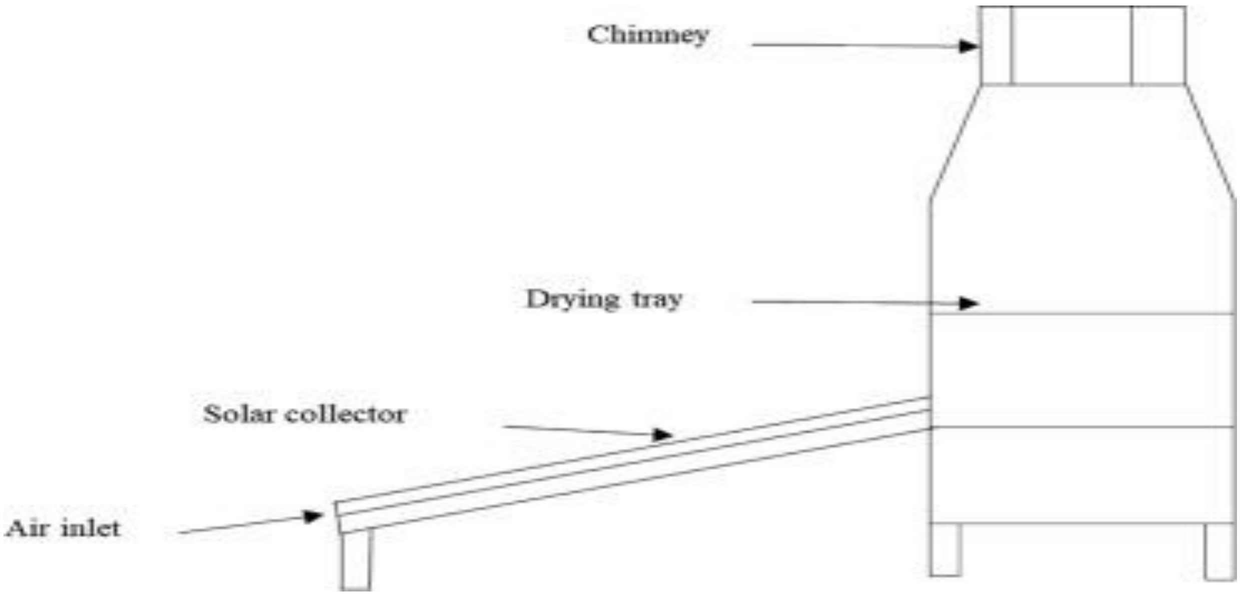

Figure 3. **Schematic overview of a ISD**
Source: MALIK and KUMAR (2022)

Mixed-mode Solar Dryers (MMSDs)

In the mixed-mode solar dryer, the solar air heater indirectly heats the drying air, while the drying chamber has transparent walls or a roof that allows direct solar radiation, as shown in Figure 4. They work on both the principles of DSDs and ISDs, which creates a synergistic effect. They have higher temperatures and are more efficient than indirect dryers (JANGDE et al., 2022; EL-MESERY et al., 2022).

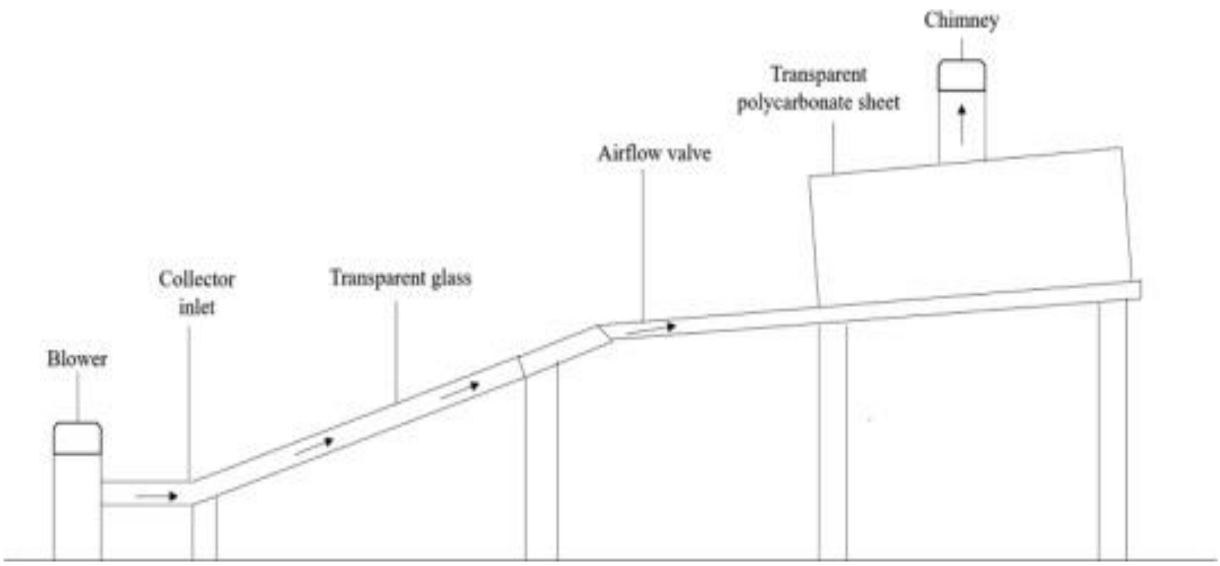

Figure 4. Schematic overview of a MMSD
Source: MALIK and KUMAR (2022)

Hybrid solar dryers (HSDs)

HSDs are based on the other classes of solar dryers. Their primary objective is to foster continuous drying. They introduce auxiliary energy sources to enable drying during cloudy weather or periods with no solar irradiation. Figure 5 provides an overview of an HSD. However, LINGAYAT et al. (2023) show that HSDs are critical in maintaining a constant drying temperature regardless of fluctuations in solar radiation. The auxiliary heat sources include biomass heaters, electric heaters, thermal storage materials, liquefied petroleum gas, and photovoltaic thermal heating. HSDs also include the integration of solar dryers with other drying technologies such as heat pumps, microwave drying, and infrared drying. Although the dryers foster continuous drying, they require high manufacturing and maintenance costs (LINGAYAT et al., 2023). The choice of a hybrid dryer also has a significant environmental impact. JHA and TRIPATHY (2021) classify hybrid dryers as renewable–renewable dryers and renewable–non-renewable dryers. The use of non-renewable auxiliary energy sources results in increased emissions of greenhouse gases.

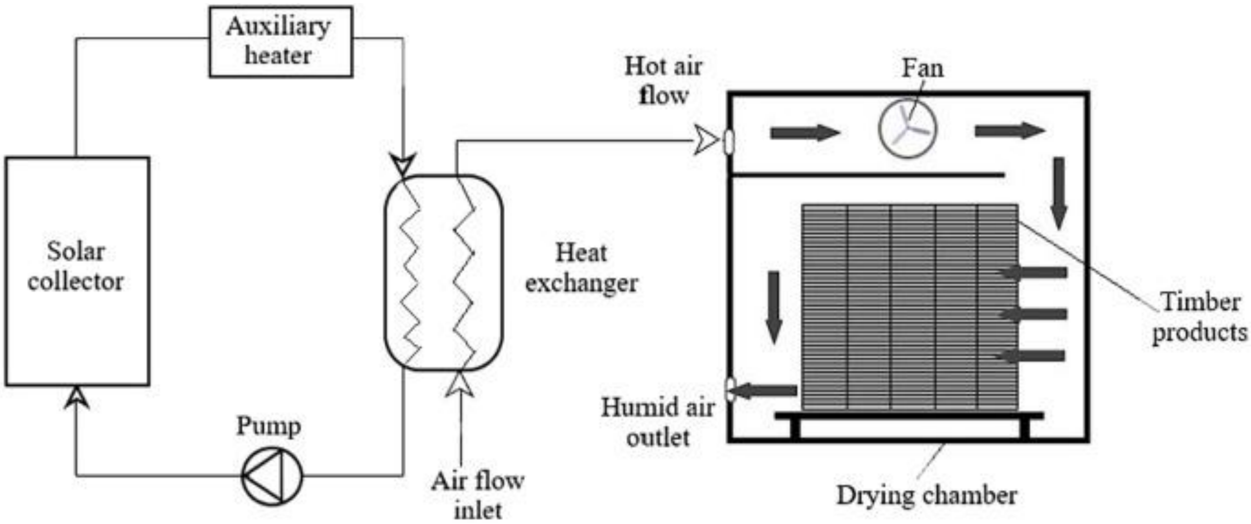

Figure 5. Schematic overview of a HSD
Source: KAMARULZAMAN et al. (2021)

Environmental Assessment

This section will focus on the environmental assessment of the DSD, ISD, and MMSD. HSD is not considered in this study as it works based on the principles of the other dryers and only incorporates an auxiliary heat source.

Material sustainability

The common materials used in solar dryers is shown in Table 1. The direct solar dryer primarily relies on a transparent cover at the top or inclined at the front of the drying section. The walls, the transparent cover, and the support of the dryer are made of different materials. MUSTAYEN et al. (2014) constructed a direct dryer that uses 1 cm thick pressed wood to make the walls of the dryer. The walls were insulated using glass wool on the inner side of the dryer. SHARMA and SHARMA (2012) also note that the entire dryer can be made of wood, as it is a good

insulator. A thick glass sheet is used as the transparent cover for the dryer. STILING et al. (2012) and CÉSAR (2020) propose the use of a transparent polycarbonate that can filter UV rays entering the dryer. Ultraviolet-treated polythene sheets can also be used to concentrate the solar radiation inside the dryer (AYUA et al., 2017; MEHTA et al., 2018).
In ISDs, all the walls of the drying section are insulated and covered to prevent direct solar radiation. In addition to the drying section, ISDs have solar air heaters that preheat the air. MUSTAYEN et al. (2014) denote that the drying section of the dryer can have the same materials as the DSD. The transparent cover of DSDs can be insulated or made opaque and used as ISDs. The air heaters consist of three essential components: transparent cover, absorber plate, and insulators. EL-SEBAEY et al. (2023) use galvanized steel as the absorber plate. The material is painted black for maximum absorption of heat. The transparent cover is made of glass. The side walls are also made of glass. The insulation material used in the air collector is sawdust. Unlike glass wool, sawdust has no carcinogenic effect. EL-SEBAEY et al. (2023) and STILING et al. (2012) propose the use of a wooden frame in the drying chamber. The sides of the dryer are made of transparent glass windows. The trays are made of wooden frames and stainless steel mesh. MAITI et al. (2011) developed an indirect dryer. The frame of the drying section was made of teak wood. The collector's outer body was made of plywood. SHARMA and SHARMA (2012) also used plywood as the outer cover of the box-shaped collector. Besides wood, Insuflex has also been used as an insulation material for collectors (DESA et al., 2023). Sunscreen fabric or 100% natural burlap has been used to cover the dryers (STILING et al., 2012). The material allows visible light to pass into the dryer but blocks ultraviolet radiation. A thermocol insulator was inserted between two plywood sheets. The absorber plate was constructed using galvanized iron sheet; the cover was made of glass. Other researchers have also developed solar collectors using galvanized materials (GEETE et al., 2021). The use of black polyethene materials as absorbers has also been employed (STILING et al., 2012).
As the MMSDs are a combination of direct and indirect heating, they use similar materials used in fabricating the drying section as in the direct solar dryer. The solar air heater materials are similar to those used in ISDs. NAYANITA et al. (2022) define that the materials mainly used to fabricate mixed-mode dryers are wood, plywood, stainless steel nets, glass, mild steel, glue, paint, and aluminum sheet.

Table 1. Common materials used in solar dryers

Component	Direct Solar Dryer	Indirect Solar Dryer	Mixed-Mode Solar Dryer
Drying chamber			
Transparent cover	glass, polycarbonate sheet, UV-treated polythene sheet	Insulated or opaque panel or glass	Same as DSD
Side walls	Wood, plywood, acrylic, galvanized steel sheet, mild steel	Same as DSD	Same as DSD
Frame	Wood, mild steel	Same as DSD	Same as DSD
Trays	Wooden furring strips with food-grade nets (stainless steel, galvanized steel, food-grade plastic)	Same as DSD	Same as DSD

Insulation materials	Glass wool, saw dust, foam board, acrylic, heatlon sheet, wood fiber, PVC, wool fiber, thermocol, polyisocyan., Insuflex,	Same as DSD	Same as DSD
Bottom/Absorber surface	Black-painted surface, concrete, pebbles, stones, polyethylene film	Same as DSD	Same as DSD
Outlet and inlet screens	Nets (stainless steel, galvanized steel, food-grade plastic)	Same as DSD	Same as DSD
Other accessories	Hinges, glue,handles, silicone, nails, paint	Same as DSD	Same as DSD
Air Collector			
Transparent cover		Glass, polycarbonate	Same as ISD
Absorber plate		Black-painted metal sheet (iron, aluminum, galvanized steel), black polyethylene/plastic sheet	Same as ISD
Side walls and insulations		Wood, foam board, glass wool acrylic, heatlon Insuflex, thermocol.	Same as ISD

Apart from the materials used in the construction of the dryers, it is essential to also consider the availability of the materials and the ease of construction. KUMAR and SINGH (2020) denote that direct solar dryers use locally available materials and are easy to construct. ISDs are more complex to construct as they entail additional components, and GUPTA et al. (2017) show that the tools mostly required to construct ISDs are electric cutter machine, mallet, hammer, wood chisel, handsaw, jack plane, pinch bar, and pincers. The construction of mixed-mode dryers is nearly the same as that of the ISDs, only that the drying section has to be modified and covered with a transparent cover. Both dryers use nearly the same materials. OGUNDANA et al. (2022) highlight the materials used as wood, glass, galvanized steel, paint, nails, and glue.

Carbon footprint

The environmental impact of solar dryers has made them popular in the drying field. Embodied energy is a key determinant in an environmental assessment of a dryer. Embodied energy refers to the total energy required to produce an item. It includes the extraction, processing, transportation, and manufacturing of the product. DESA et al. (2023) show that the embodied energy in constructing the collector is higher than in any other section of the dryer. The researchers further found that the embodied energy of constructing a collector and drying chamber was 397.55 kWh and 209.3 kWh, respectively, in a mixed-mode dryer. The acrylic material used to construct the walls of the drying chamber has higher embodied energy when compared to the materials used for constructing an opaque chamber for ISD. This means that when using similar materials, ISDs will have lower embodied energy compared to MMSDs. The metal absorber used in the dryer contributes significant embodied energy to the construction of a dryer. DESA et al. (2023) also showed that aluminum contributed 66% of the total embodied energy used to construct a mixed-mode solar dryer. The choice of material also plays a significant role in determining the total energy required in the construction of a dryer. The higher embodied energy correlates with the amount of emissions generated by a dryer in manufacturing.

As embodied energy only focuses on the construction of the dryer, it is essential to investigate the entire lifecycle of the dryers to determine which one causes more harm to the environment. NAYANITA et al. (2022) conducted a life cycle assessment of direct and mixed-mode solar dryers used to dry 20 kg of garlic and found that MMSDs have 43% more impact on climate change and resource depletion when compared with DSDs. The researchers further found that MMSDs have adverse impacts not only on resources but also on human health and the ecosystem when compared with DSDs. HAO et al. (2025) also noted that MMSDs have a higher environmental impact than DSDs. DSDs are constructed using readily available materials that aid in reducing emissions due to extraction, processing, and manufacturing. Their environmental impact relies mainly on the operation of the dryer. However, constructing the solar air heater requires additional materials and processes, which increases the carbon footprint associated with MMSDs.

Energy and drying efficiency

The mixed-mode dryer has superior performance as far as drying efficiency is concerned. The drying chamber of the MMSD has the highest temperature when compared with the other dryers due to the combined effects of direct and indirect heating. LAKSHMI et al. (2019) investigated drying white turmeric using indirect and mixed-mode solar dryers. The dryers use the same technology in air heating and have a similar dryer size. The researchers found that the drying chamber of the MMSD was 47.7°C while that of the ISD was 36.1°C. The high drying temperature made the MMSD have 4.7% more drying efficiency than the ISD. DEJCHANCHAIWONG et al. (2016) further recorded higher temperatures in the drying chamber of the MMSD when compared with the ISD. The researchers recorded the drying efficiency of the MMSD as 15.4% while that of the ISD was 13.3%. HAO et al. (2025) also found MMSDs to have higher thermal efficiency due to their application of two heating sources. Due to the high temperature in the drying chamber, MMSDs have a lower drying time when compared with DSDs. NAYANITA et al. (2022) show that active MMSDs take only 48.4% of the time taken to dry 20 kg of ginger using passive DSDs. It has also been found that MMSDs have higher drying rates than ISDs at any airflow speed (GHATREHSAMANI et al., 2012). MMSDs are more efficient in enhancing solar drying. However, the efficiencies of the dryers are quite low, and there is a need for further studies to improve the efficiencies of the existing dryers.

Comparative analysis

Table 2 provides a comparative environmental assessment of direct, indirect, and mixed-mode dryers using different criteria.

Table 2. A comparative analysis of DSD, ISD, and MMSD

Criteria	DSD	ISD	MMSD
Material sustainability	• Use locally available materials • Easy to construct and maintain	• Uses more materials, which may not be readily available. • More efforts are required in the construction of the collector.	• Higher materials usage due to the combination of DSD and ISD. • More work is needed in developing the drying system
Carbon footprint	• Low	• Moderate due to more components	• Highest footprint due to complex structures and additional construction
Embodied energy	• lower	• moderate	• Highest
Environmental impact	• lower	• moderate	• Highest
Drying and energy efficiency	• Lower efficiency • Long drying hours	• Moderate efficiency • moderate drying hours	• Highest efficiency • Shortest drying hours
Suitability for rural areas	• Highest (simple construction)	• Low due to the complex construction of collector	• Low due to complex construction.

The three dryers have distinct variations as far as environmental sustainability is concerned. There is a need to foster a delicate balance between the performance of the dryers and their environmental impact. The environmental impact of MMSD and ISD is nearly the same, depending on the transparent materials used in the former technology. As a result, it is vital to select the drying method based on the desired outcomes. However, SINGH and GAUR (2024) have shown that solar dryers have better performance than conventional dryers, including open sun drying. As a result, there is a need to take advantage of the synergistic effects of MMSD and maximize their outputs while taking into account aspects such as material sustainability and carbon footprint.

Limitations of the Study

- The study assumes simple designs, such as flat plate collectors, and ignores other collector types that may have a significant impact on thermal performance and environmental impact.
- The study assumes similar materials for the dryers, which is not a true representation of real-world conditions. Different materials exist based on regions, and they affect factors such as construction cost and embodied energy.
- The study focuses only on embodied energy and does not address other critical aspects such as lifetime emissions, disposal phase, and maintenance frequency.

Challenges and Research Opportunities

- Indirect and mixed-mode dryers show superior performance, but they require additional and complex components that make them unaffordable for rural farmers.

- Rural dwellers also lack the technical know-how to develop and maintain ISDs and MMSDs.
- Although DSDs are easy to construct, there is limited control over temperature and UV radiation, which affect thermal performance and product quality.
- None of the dryers guarantee continuous drying. There is a need to incorporate other hybrid solutions to account for low solar irradiance.
- MMSDs offer higher efficiency but have higher carbon footprints and embodied energy, which make them less sustainable.
- There is a need for further research to develop localized, low-cost materials that will enable the application of MMSDs and ISDs in rural settings.
- There is a need to develop replicable designs that can easily be reproduced using the tools and materials available in remote areas.
- Further studies are needed on readily available thermal storage solutions that can be integrated into the dryers to foster thermal performance even during cloudy weather and at night.
- There is a need for real-world testing of DSD, ISD, and MMSD under similar conditions to collect performance and environmental data.

Conclusion

The present study comprehensively assessed the environmental impacts of direct, indirect, and mixed-mode solar drying. The environmental assessment is based on material sustainability, carbon footprint, and drying and energy efficiency. Each dryer has its limitations and strengths, which affect its suitability in various contexts.

DSDs use local materials and are simple to construct. They are also eco-friendly due to their simple construction and use of readily available materials. However, these dryers have many limitations that make them unsuitable for drying food crops. They have limited temperature control, making it difficult to enhance drying performance. Direct solar drying also harms product quality due to ultraviolet radiation directly heating the food products. ISDs offer better product control as the food materials are shielded from direct solar radiation. They also provide better temperature control. However, they include additional components that increase construction costs, making them inaccessible to small-scale farmers in rural settings. MMSDs harness the benefits of both direct and indirect solar dryers. They have the highest drying efficiency and shorter drying durations due to the high temperatures recorded in the drying chamber. However, MMSDs have the largest environmental impact because of the high embodied energy associated with them.

Each dryer has demonstrated its strengths and limitations. MMSDs have superior performance compared to the other dryers; however, their sustainability poses challenges due to the complexity of their systems and the associated carbon footprint and embodied energy. There is a need to improve designs and incorporate low-impact materials. The performance of the dryers can also be enhanced by integrating thermal storage systems and harvesting exhaust gases to preheat the drying air. Although MMSDs have better efficiency, selecting the right type of dryer based on prevailing conditions is essential. There is a need to strike a balance between environmental impacts, performance demands, and local feasibility. Further studies are required to develop simple designs using locally available and eco-friendly materials. Solar dryers are a promising tool for addressing post-harvest losses and fostering environmental sustainability.

References

AYUA, E. – MUGALAVAI, V. – SIMON, J. – WELLER, S. – OBURA, P. – NYABINDA, N. (2017): Comparison of a mixed modes solar dryer to a direct mode solar dryer for African indigenous vegetable and chili processing. *Journal of Food Processing and Preservation*, *41*(6), e13216. https://doi.org/10.1111/jfpp.13216

BALASUADHAKAR, A. (2021): A review of construction, material and performance in mixed mode passive solar dryers. Materials Today: Proceedings, 46, 4165–4168. https://doi.org/10.1016/j.matpr.2021.02.679

CÉSAR, L.V.E. – LILIA, C.M.A. – OCTAVIO, G.V. – ISAAC, P.F. – ROGELIO, B.O. (2020): Thermal performance of a passive, mixed-type solar dryer for tomato slices (Solanum lycopersicum). *Renewable Energy*, *147*, 845–855. https://doi.org/10.1016/j.renene.2019.09.018

DEEPAK, C.N. – BEHURA, A.K. (2023): Critical Review on Various Solar Drying Technologies: Direct and Indirect Solar Dryer Systems. Applied Solar Energy, 59(5), 672–726. https://doi.org/10.3103/S0003701X2360073X

DEJCHANCHAIWONG, R. – ARKASUWAN, A. – KUMAR, A. – TEKASAKUL, P. (2016): Mathematical modeling and performance investigation of mixed-mode and indirect solar dryers for natural rubber sheet drying. *Energy for Sustainable Development*, *34*, 44–53. https://doi.org/10.1016/j.esd.2016.07.003

EL-MESERY, H.S. – EL-SEESY, A.I. – HU, Z. – LI, Y. (2022): Recent developments in solar drying technology of food and agricultural products: A review. *Renewable and Sustainable Energy Reviews*, *157*, 112070. https://doi.org/10.1016/j.rser.2021.112070

EL-SEBAEY, M.S. – MOUSAVI, S.M. – EL-DIN, S.S. – ESSA, F.A. (2023): An experimental case study on development the design and the performance of indirect solar dryer type for drying bananas. *Solar Energy*, *255*, 50–59. https://doi.org/10.1016/j.solener.2023.03.023

FERNANDES, L. – TAVARES, P.B. (2024): A review on solar drying devices: Heat transfer, air movement and type of chambers. *Solar* 4(1) 15–42. https://doi.org/10.3390/solar4010002

GEETE, A. – SINGH, Y. – RATHORE, S. (2021): Energy and exergy analyses of fabricated solar drying system with smooth and rough surfaces at different conditions: A case study. *Heat Transfer*, *50*(6), 6259–6284. https://doi.org/10.1002/htj.22171

GHATREHSAMANI, S.H. – DADASHZADEH, M. – ZOMORODIAN, A. (2012): Kinetics of apricot thin layer drying in a mixed and indirect mode solar dryer. *International Journal of Agriculture Sciences*, *4*(6), 262. https://doi.org/10.9735/0975-3710.4.6.262-267

GUPTA, P.M. – DAS, A.S. – BARAI, R.C. – PUSADKAR, S.C. – PAWAR, V.G. (2017): Design and construction of solar dryer for drying agricultural products. *International research Journal of engineering and technology*, *4*(3), 1946.

HAO, W. – WANG, X. – LIU, W. – MA, J. – LIU, C. – WANG, L. (2025): Research on the performance and life cycle assessment of photovoltaic/thermal hybrid solar dryer: Comparative analysis with direct and mixed-mode. *Applied Thermal Engineering*, *272*, 126425. https://doi.org/10.1016/j.applthermaleng.2025.126425

HIDALGO, L.F. – CANDIDO, M.N. – NISHIOKA, K. – FREIRE, J.T. – VIEIRA, G.N.A. (2021): Natural and forced air convection operation in a direct solar dryer assisted by photovoltaic module for drying of green onion. Solar Energy, 220, 24–34. https://doi.org/10.1016/j.solener.2021.02.061

JANGDE, P.K. – SINGH, A. – ARJUNAN, T.V. (2022): Efficient solar drying techniques: a review. Environmental Science and Pollution Research, 29(34), 50970–50983. https://doi.org/10.1007/s11356-021-15792-4

JHA, A. – TRIPATHY, P.P. (2021): Recent advancements in design, application, and simulation studies of hybrid solar drying technology. *Food Engineering Reviews*, *13*, 375–410. https://doi.org/10.1007/s12393-020-09223-2
KAMARULZAMAN, A. – HASANUZZAMAN, M. – RAHIM, N.A. (2021): Global advancement of solar drying technologies and its future prospects: A review. *Solar Energy*, *221*, 559–582. https://doi.org/10.1016/j.solener.2021.04.056
KHALIL, A. – KHAIRA, A.M. – ABU-SHANAB, R.H. – ABDELGAIED, M. (2023): A comprehensive review of advanced hybrid technologies that improvement the performance of solar dryers: Photovoltaic/thermal panels, solar collectors, energy storage materials, biomass, and desalination units. *Solar Energy*, *253*, 154–174. https://doi.org/10.1016/j.solener.2023.02.032
KUMAR, P. – SINGH, D. (2020): Advanced technologies and performance investigations of solar dryers: A review. *Renewable Energy Focus*, *35*, 148–158. https://doi.org/10.1016/j.ref.2020.10.003
LAKSHMI, D.V. – MUTHUKUMAR, P. – EKKA, J.P., NAYAK, P.K. – LAYEK, A. (2019): Performance comparison of mixed mode and indirect mode parallel flow forced convection solar driers for drying Curcuma zedoaria. Journal of Food Process Engineering, 42(4), e13045. https://doi.org/10.1111/jfpe.13045
LINGAYAT, A. – DAS, P. – GILAGO, M.C. – CHANDRAMOHAN, V.P. (2023): A detailed assessment of paraffin waxed thermal energy storage medium for solar dryers. *Solar Energy*, *261*, 14–27. https://doi.org/10.1016/j.solener.2023.05.047
MAITI, S. – PATEL, P. – VYAS, K. – ESWARAN, K. – GHOSH, P.K. (2011): Performance evaluation of a small scale indirect solar dryer with static reflectors during non-summer months in the Saurashtra region of western India. *Solar Energy*, *85*(11), 2686–2696. https://doi.org/10.1016/j.solener.2011.08.007
MALIK, A. – KUMAR, M. (2022): A review on turmeric drying technologies. *Materials Today: Proceedings*, *62*, 5358–5364. https://doi.org/10.1016/j.matpr.2022.03.539
MEHTA, P. – SAMADDAR, S. – PATEL, P. – MARKAM, B. – MAITI, S. (2018): Design and performance analysis of a mixed mode tent-type solar dryer for fish-drying in coastal areas. *Solar energy*, *170*, 671–681. https://doi.org/10.1016/j.solener.2018.05.095
MUSTAYEN, A.G.M.B. – MEKHILEF, S. – SAIDUR, R. (2014): Performance study of different solar dryers: A review. *Renewable and Sustainable Energy Reviews*, *34*, 463–470. https://doi.org/10.1016/j.rser.2014.03.020
NAYANITA, K. – SHAIK, S.R. – MUTHUKUMAR, P. (2022): Comparative study of mixed-mode type and direct mode type solar dryers using life cycle assessment. Sustainable Energy Technologies and Assessments, 53, 102680. https://doi.org/10.1016/j.seta.2022.102680
OGUNDANA, O.S. – JUNEID, Y.M. – OLAIFA, O.P. – OWA, T.W. (2022): Design, construction and evaluation of solar dryer. *Journal of Modern Science and Technology*, 7(1–2):1–5.
SHARMA, A. – SHARMA, N. (2012): Construction and performance analysis of an indirect solar dryer integrated with solar air heater. *Procedia Engineering*, *38*, 3260–3269. https://doi.org/10.1016/j.proeng.2012.06.377
SINGH, P. – GAUR, M.K. (2024): Review on development, recent advancement and applications of various types of solar dryers. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *46*(1), 14471–14491. https://doi.org/10.1080/15567036.2020.1806951
STILING, J. – LI, S. – STROEVE, P. – THOMPSON, J. – MJAWA, B. – KORNBLUTH, K. – BARRETT, D.M. (2012): Performance evaluation of an enhanced fruit solar dryer using concentrating panels. *Energy for sustainable development*, *16*(2), 224–230. https://doi.org/10.1016/j.esd.2012.01.002

TIWARI, A. (2016): A review on solar drying of agricultural produce. *Journal of Food Processing & Technology*, *7*(9), 1–12. https://doi.org/10.4172/2157-7110.1000623
WATSON, A.G. – MUJUMDAR, A.S. – THORAT, B.N. – SHIRKOLE, S.S. – BHATKAR, N.S. (2024): A simple solar crop drying and pasteurizing system appropriate for smallholder and subsistence farmers in tropical and subtropical regions. *Drying Technology*, *42*(3), 407–422. https://doi.org/10.1080/07373937.2023.2182316

Authors

Abraham Kiprop Juma
PhD student, Corresponding author
Hungarian University of Agriculture and Life Sciences, Gödöllő, Szent István Campus
Doctoral School of Mechanical Engineering, Pater K. u. 1, Gödöllő, H-2100, Hungary
juma.abraham.kiprop.2@phd.uni-mate.hu

Dr. Zoltán Kurják PhD.
associate professor
Hungarian University of Agriculture and Life Sciences, Gödöllő, Szent István Campus
Institute of Technology, Gödöllő, H-2100, Hungary

Dr. János Beke PhD.
professor
Hungarian University of Agriculture and Life Sciences, Gödöllő, Szent István Campus
Institute of Technology, Gödöllő, H-2100, Hungary