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Modification approach of Northern Wall to improve the performance of solar greenhouse dryers: A review

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ABSTRACT

Globally, interest is shifting toward green energy due to its environmental appeal. Therefore, to promote energy and environmental conservation in drying, several solar dryers have been developed which offers limitless, clean, and free energy to dry agricultural product. Among these solar dryers, solar greenhouse dryers offer a very simple low-temperature, energy-efficient structure capable of drying large beds of crops by harnessing thermal radiation energy from the sun. To improve the thermal performance in the passive mode especially, several modification approaches have been adopted. This article, therefore, reviewed various possible modification methods that have been adopted to improve the thermal performance of the greenhouse, with a focus on the modification of the northern wall. The various strategies involved in the modification of the north wall structure include creating an opaque north wall with black painted materials, installing a reflective north wall using a mirror, integrating heat storage materials like pebbles or brick, integrating phase change materials into the north wall, digging the soil depth to form a north wall and creating a variable southern roof with a modified north wall. Modifying the northern wall showed higher drying chamber temperature compared to completely transparent convectional greenhouse dryers in all the studies. These modifications can increase the temperature of the modified greenhouse by 13.38~21.10% for a natural convection solar greenhouse dryer compared to the conventional type. With this approach, the radiation losses from the northern wall can be minimized and the energy management system of the greenhouse can be optimized for higher performance, making it more sustainable and eliminating the use of fossil fuel in agricultural product drying.

1. Background

Drying is an energy-consuming process that generates a lot of carbon emissions when the predominant fossil fuel-based dryers are used (Ndukwu et al., 2018). Thus, It becomes imperative to reduce energy utilization in the drying process to improve the environment. Transitioning from fossil fuel dryers to low-carbon or net zero-carbon dryers will help mitigate climate change and reduce its effect on the global ecosystem. Hence, there is a global shift in interest toward green energy due to its environmental appeal. Among these alternative renewable energy sources, solar drying is the least costly, and it offers limitless, clean, and free energy with comparatively low investment for drying agricultural products (Ramde and Forson, 2007). Therefore, several solar dryers have been developed to replace fossil energy-based dryers (Ndukwu et al., 2018). The design can be of direct cabinet type (Ndukwu et al., 2023a), indirect or mix-mode (Ndukwu et al., 2022a, 2022b), hybrid (Ndukwu and Bennamoun, 2018 and Ndukwu et al., 2020a, 2022c) and direct solar greenhouse type (Chauhan and Kumar, 2016) as shown in Fig. 1. A solar greenhouse dryer can be described as a structure

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Nomenclature

A_{tray}	Cross-sectional area of the tray (m^2)
A_i	The cross-sectional area of the inlet hole (m^2)
A_{vent}	Cross-sectional area of vent (m^2)
I_{gr}	Global solar radiation (W/m^2)
ΔP	Partial pressure difference between room temperature and ambient air (N/m^2)
Rha	Ambient relative humidity (%)
T_{room}	Temperature inside the North wall insulated greenhouse dryer (°C)
T_a	Ambient temperature (°C)
$T_{be}d$	bed temperature (°C)
U	Heat loss coefficient (W/m^2 °C)
ρ	Density of humid air (kg/m^3)

covered with transparent (glazing) cladding materials that uses the greenhouse gas effect (Fig. 2) i.e. the trapping of the solar radiation in a greenhouse atmosphere, due to its greater transparency to visible radiation from the sun rays than to infrared radiation emitted from the absorber or its bed surface.

Thus, the greenhouse gas within the enclosure consumes this energy and in turn emits thermal energy within the enclosure, thereby generating heat to dry biomaterials. This kind of structure has been used for lower-temperature large-scale solar drying for ages (Prakash and Kumar, 2014). The products are usually placed on wire mesh shelves or an elevated platform inside the greenhouse (Kumar and Tiwari, 2006). The cover or the cladding materials are supported with a frame that can be made of wood, blocks, or metals.

1.1. Types of green house covering materials

The covering materials (Fig. 3) are very important and must be chosen based on availability, reliability, cost, transparency to shortwave radiation, and material thermal conductivity. Among cladding materials used for greenhouse dryer development include tempered glass, silica glass, Basla, polyolefin, PVC film, polycarbonate, plastic films, and polythene. The materials should also exhibit low thermal conductivity (Al-Mahdouri et al., 2013). One of the properties of greenhouse glazing materials is that they must be transparent to short wavelength radiation from the sun rays but will be opaque to the long wave radiation emitted from the greenhouse gases or absorbing materials.

Thus, the thermal energy emitted from the greenhouse gases or the absorber which is of long wave radiation will be prevented from leaving the greenhouse, leading to the increase in the surface temperature. If this process occurs outside the greenhouse, it might become a subject of concern due to the tendency to increase global warming, but within the enclosure of the greenhouse structure, it becomes useful in the drying of crops.

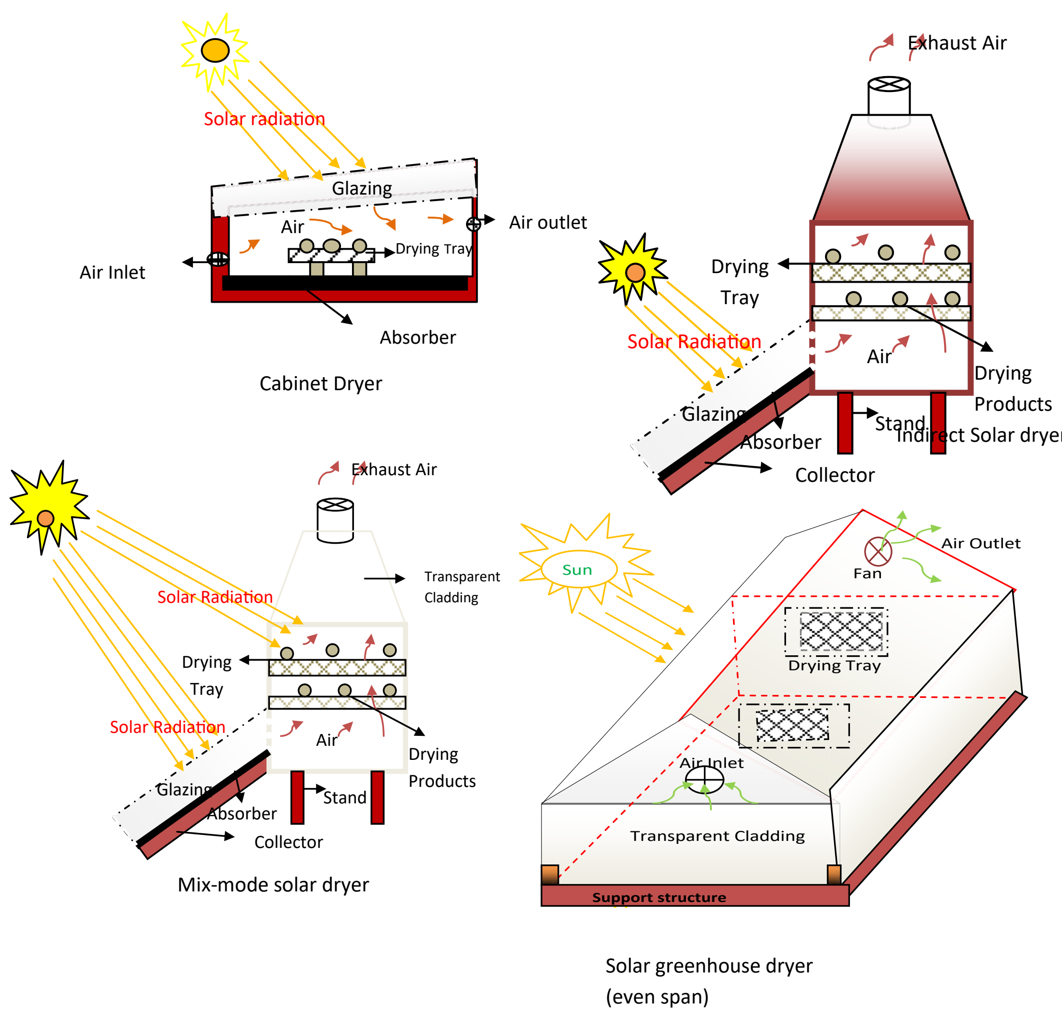

Fig. 1. Different types of solar dryers.

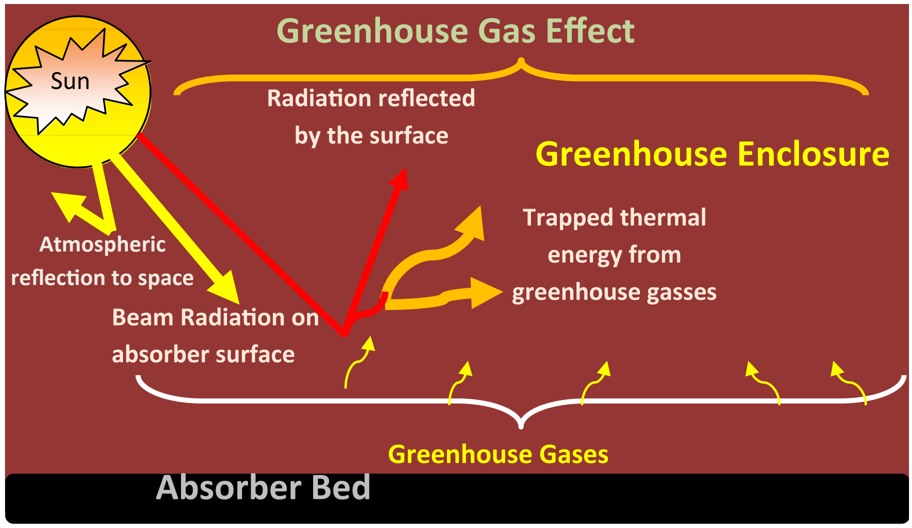

Fig. 2. Greenhouse gas effect in a solar greenhouse.

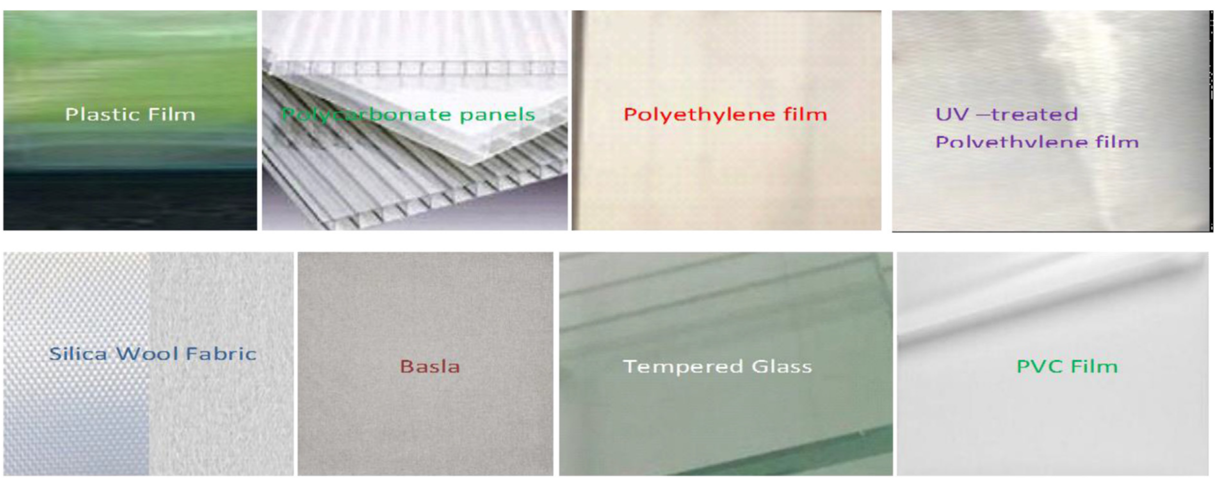

Fig. 3. Pictures of some greenhouse cover materials.

1.2. Various shapes of greenhouse

Geometric shape and orientation are major factors in the operation of greenhouse dryers. Therefore, various shapes of greenhouse design exist and these shapes and their orientations are of great importance in the performance of a greenhouse (El-Afou et al., 2015). The various shapes of the greenhouse investigated in literature are presented in Fig. 4(a)–(c). They include even span, uneven span, parabola, vinery, modified arch, igloo, single span, tropical, semi-circular, elliptical, pyramid gothic, gable, geodesic dome, single slope, mansard roof, Chapel shape, Quonset shapes, and modified Quonset. Cakır and Sahin (2015) also presented elliptical shapes, while Gupta and Chandra (2002) reported gothic shapes too. These greenhouses can be oriented in the east-west, or north-south directions (Cakır and Sahin, 2015). However, it was observed that the East-west orientation is preferred because of the highest radiation reception and lower heat losses which have been reported in literature (Gupta and Tiwari, 2005; Dragicevic, 2011).

1.3. Motivation for the review

Literature showed that general reviews on solar greenhouse dryers have been presented in the literature (Singh et al., 2018; Srinivasan and Muthukumar, 2021, Ndukwu, 2023) but the impact of modification of the northern wall on passive greenhouse solar dryers was not highlighted in detail. Modifying the northern wall in solar greenhouses significantly enhances thermal performance, particularly during cold periods. When the greenhouse is positioned in the northern hemisphere, modifying the northern wall is crucial due to the minimal solar radiation the northern wall receives, especially during the winter. Thus, the northern wall becomes a conduit for increased thermal losses, and poses higher condensation and frost risk. Modification of this side of the greenhouse to prevent these losses from occurring has been shown to improve the energy performance of passive solar greenhouse dryers and help the solar dryers operate optimally (Chauhan and Kumar 2018). For example, creating an opaque or reflective north wall in a solar greenhouse located in the north of the equator offers several advantages, which include reduced heat loss, increased thermal mass, and improved energy efficiency by minimizing conduction through the wall; enhanced natural lighting by reflecting sunlight from the south into the greenhouse; reduced shading from structural elements and potential for integrating thermal storage materials, such as concrete or brick, to absorb and release heat. This design also allows for better insulation, and minimized frost damage, ultimately contributing to a more stable, energy-efficient, and productive greenhouse environment. Thus the present study seeks to highlight various modification approaches of solar greenhouse dryers and presents some useful data on results obtained from various research to broaden knowledge in this area. The review contents are presented according to the chart presented in Fig. 5.

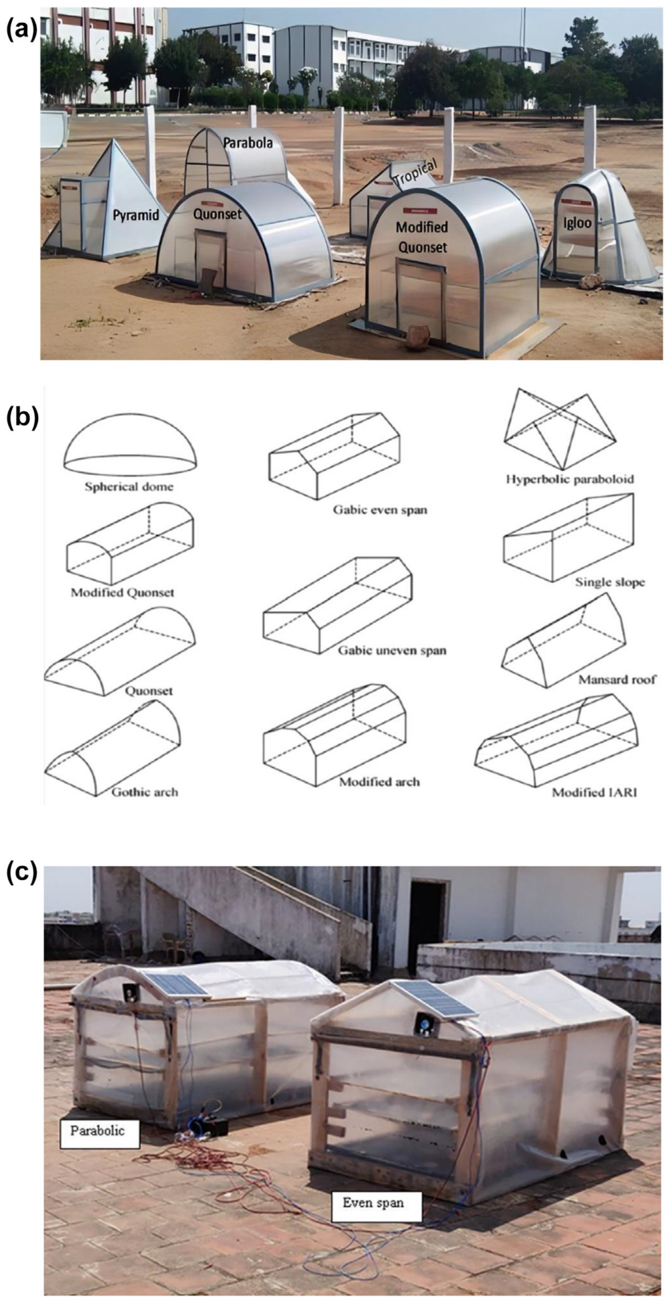

Fig. 4. (a) Different greenhouse shapes (Pyramid, Quonset, Tropical, Igloo, Modified Quonset, and Parabola. ref, Mobtaker et al., 2019). (b) Different greenhouse shapes (modified arch, single slope, mansard roof, gothic arch, etc. ref. Srinivasan and Muthukumar, 2021; Vivekanandan et al., 2021). (c) Different greenhouse dryer shapes (Parabolic and even Span. ref., Mani and Thirumalai Natesan, 2021).

2. Dynamics of heat transfer in solar greenhouse dryer

The dynamics of the energy interaction in the solar greenhouse dryer involves solar radiation, the air convection within and outside the greenhouse which can either be forced or by natural convection, conductive heat from the enclosure materials, etc. (Liu et al., 2019) as shown in Fig. 6.

Increasing the thermal performance of the greenhouse dryer can be achieved through active or passive heating. The active heating includes the use of a thermal collector with an absorber (Figs. 7 and 8), earth-air heat exchanger, or ground geothermal water while the passive improvement includes the use of a thermal curtain, rock or concrete bed, phase change materials, the modification of the northern wall, etc. (Nayak and Tiwari, 2008). Therefore, when the solar dryer is located in the northern hemisphere, the energy transfer mode consists of heat released from the absorber or the bed, heat loss dynamics of the northern wall, and any thermal storage material involved. A northern wall is formed when the greenhouse is positioned in the east-west orientation in the northern hemisphere. Research has shown that this orientation forming a northern wall of a greenhouse affects the thermal performance inside the greenhouse dryer.

The major driver of the heat and mass transfer in solar greenhouse dryers apart from the relative humidity and the temperature of the heat transfer fluid is the velocity of the heat transfer fluid. During the drying process, moisture is lost from the crop to its surrounding air. The speed at which moist air is evacuated determines its replenishment to absorb more moisture to continue the drying process. Thus, the solar greenhouse dryer deploys either passive mode with natural convection or active mode with a fan or blower powered by external power sources like solar panels, electricity, or wind energy as shown in Fig. 9. Hence, even when the northern wall is modified, the type of convection also affects the rate of heat and mass transfer as has been shown by Chauhan and Kumar (2018). This study therefore discusses the modification methods of the northern wall on the overall heat transfer dynamics and performance of the greenhouse dryer.

3. Classification of solar greenhouse

Although solar greenhouse dryers can broadly be classified as direct solar dryers and can adopt active or passive modes of air delivery to the drying chamber, however, several techniques or strategies have been used to enhance their performance (Singh et al., 2018). This depends on the variety of methods which has been investigated in the literature for effectiveness or improved performance. Thus, improvement of solar greenhouse has been investigated based on various geometric shapes, mode of air delivery to the drying chamber, improvement based on additional heating method, the type of bed, the type of modification done on the wall or roof, and the type of cladding materials used (Singh et al., 2018). This can serve as various ways in which solar greenhouse dryers can be classified. Therefore, Fig. 10 shows various classifications of solar greenhouse dryers based on existing designs in the literature. In terms of geometric shapes, different shapes have been tried in different locations to track the sun angle for receiving high solar radiation intensity into the greenhouse, while the mode of air delivery affects the rate at which evaporated moisture is removed from the greenhouse chamber. Passive greenhouse dryers use the buoyancy effect as the heated air rises towards the exits while the active mode uses mechanical air drivers like fans or blowers. In some cases, additional heating improvement has been supplemented to assist the greenhouse which involves active heating when collectors are integrated or geothermal ground water is used. On the other hand, passive supplementary heating has been adopted that includes the use of heat storage material and modification of the northern wall as shown in Fig. 9. This review focused on the classifications based on heating improvement through the modification of the northern wall.

4. The dynamics of the northern wall in a northern hemisphere

The northern wall can be formed when the greenhouse is positioned in the east-west orientation (Fig. 11) as mentioned earlier in the northern hemisphere. When this happens at some time of the year, especially in the cold or winter season, the sun stays in the southern part of the greenhouse according to Gupta and Chandra (2002). The implication is that the northern side of the transparent cladding receives little or no solar radiation but serves as an exit for the solar radiation heat incident from the southern side. Thus the northern wall becomes the path for net heat loss from the greenhouse. In some cases, if the wall is so large the heat loss from the northern wall can amount to the half of overall heat loss for the entire greenhouse (Tiwari and Amita, 2002). To quantify the

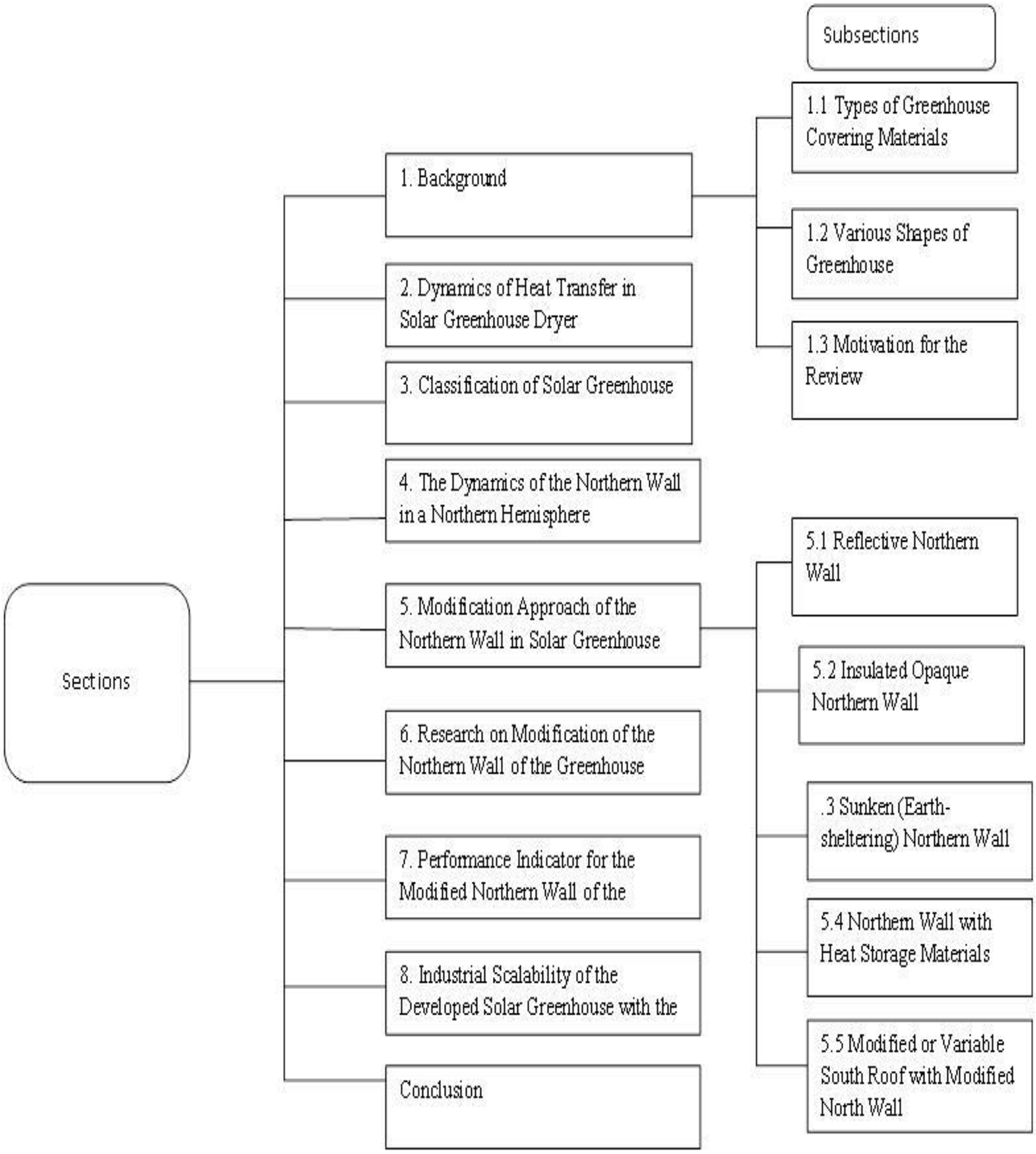

Fig. 5. Review contents.

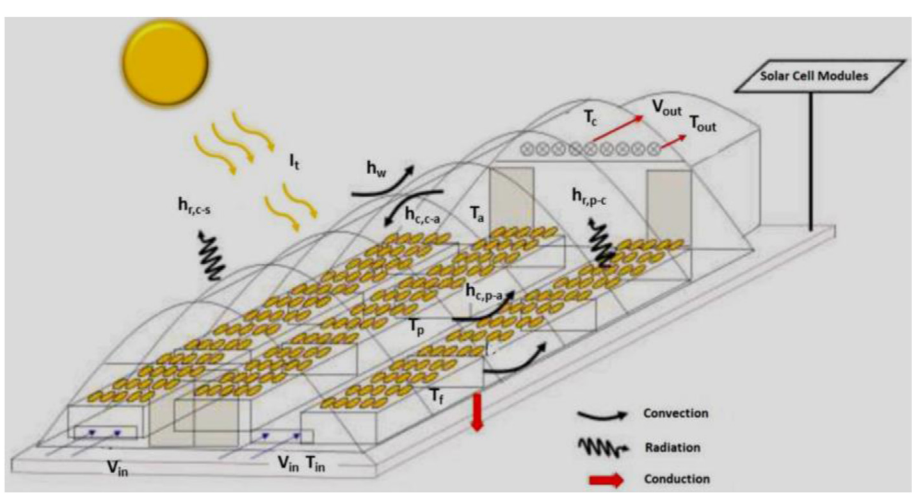

Fig. 6. Schematic diagram of energy transfers inside the solar greenhouse dryer (Nimnuan and Nabnean, 2020).

Fig. 7. Active even-span house dryer with evacuated tube collector (Singh and Gaur, 2021).

Fig. 8. Active Chapel shape greenhouse dryer (EL Khadraoui et al., 2019).

magnitude of the loss from the northern wall researchers use the term solar fraction. Hence it has been noted that the solar fraction is higher in the cold period due to the sun's angle being closer to the Earth (Tiwari and Amita, 2002; Berroug et al., 2011).

Therefore, several researchers have developed different kinds of solar greenhouse dryers with the modification of the northern wall (Jain, 2005; Chauhan and Kumar, 2016). The following sections explore various modification approaches of the solar greenhouse northern wall that can be adopted to improve performance.

5. Modification approach of the northern wall in solar greenhouse dryers

Researchers have found that the structural modification of green house's northern wall can create a suitable environment to achieve the desired heating level in the greenhouse either for crop growth, drying, or energy consumption management (Chen, 2001; Hassanain et al.;, 2011; Yu et al., 2018; Zhang et al., 2019). Since the solar intensity comes from the south when the greenhouse is placed in the northern hemisphere during the winter or cold periods in some areas, it is believed that the

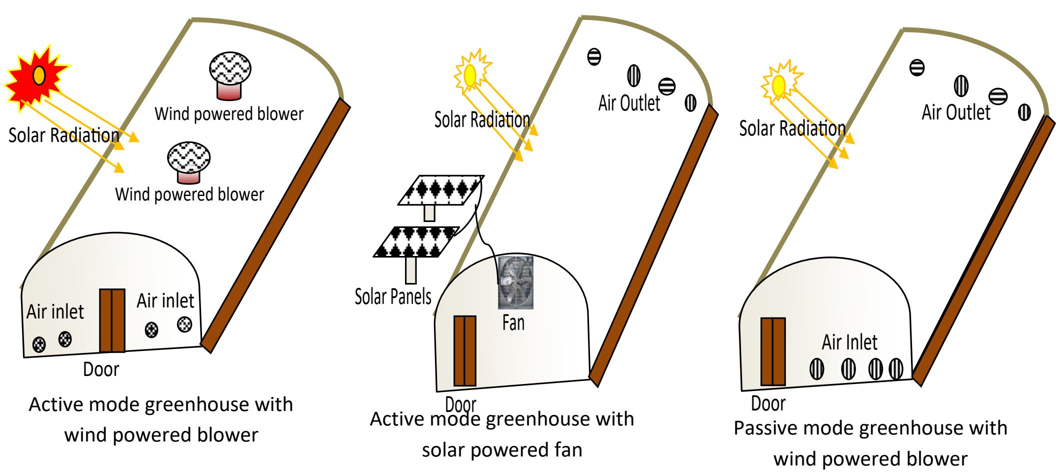

Fig. 9. Solar greenhouse operating at different convective modes.

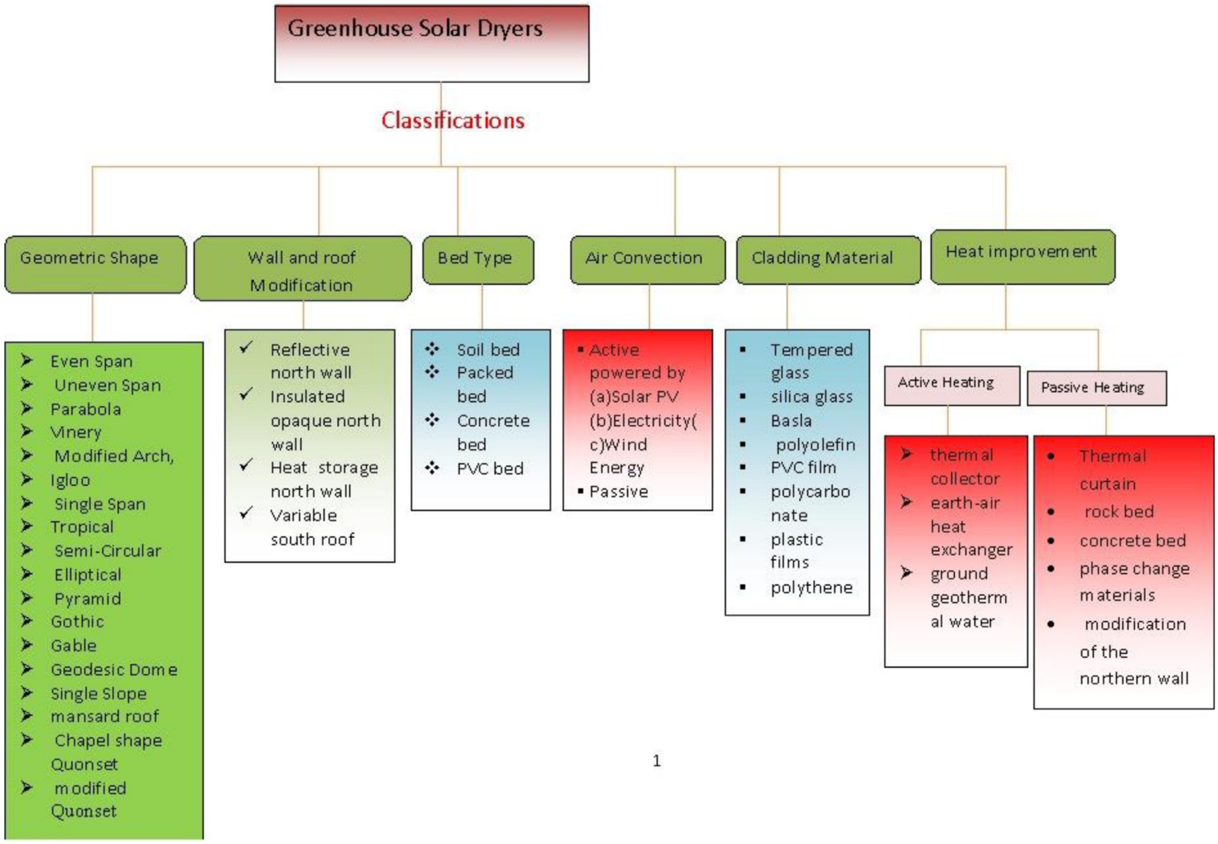

Fig. 10. Classifications of solar greenhouse.

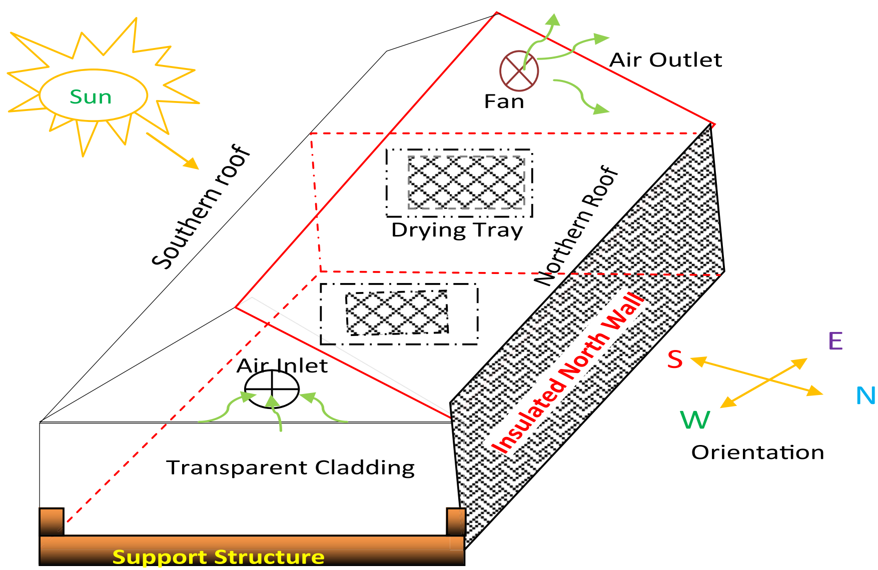

Fig. 11. Orientation of Greenhouse to show a northern wall.

northern wall can serve as energy storage by absorbing a large amount of energy which it is capable of releasing during off sunshine periods. The north wall serves several functions in the solar greenhouse that include insulation, compensation for the drying chamber temperature, and also as passive heat storage for solar radiation. According to some researchers (Ling et al., 2019; Han et al., 2024), the northern wall of a solar greenhouse can release heat during off-sunshine periods capable of raising the indoor temperature of a greenhouse by 1–10°C which is 1.4 times higher than the thermal effect generated by the ordinary soil bed. This degree rise in temperature is enough to create a temperature differential between the crop and the drying environment to allow moisture removal in crops. Therefore, improving the thermal capacity of the north wall of a solar greenhouse dryer is a way of ensuring continuous drying during off sunshine periods especially during the night. This aspect is very important, because crops are hygroscopic and are capable of reabsorbing moisture during the night (Lamrani et al., 2022; Ndukwu et al., 2023c).

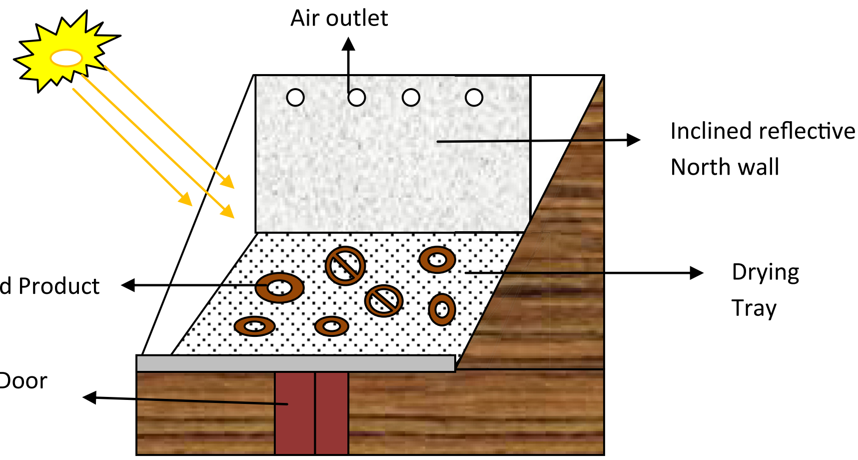

Fig. 12. Inclined reflective north wall solar greenhouse dryer.

This will prolong the drying periods and might lead to mold growth on the crops (Onyenwigwe et al., 2023a, 2023b). Thus, the structure will be such that the heat transfer coefficient should be low and quantified with good thermal insulation to reduce heat loss (Liu et al., 2019). This placed the material requirements in the development of the northern wall of the solar greenhouse dryer as a priority, especially in the night or off-sunshine periods when the bulk of heat needed to continue the drying process might come from the modified northern wall. Additionally, due to the limitation in the thermal conductivity, specific heat capacity, and heat storage capacity of materials for the northern wall, several modification methods have been made by researchers to achieve this as follows:

5.1. Reflective northern wall

Several researchers have tried to reflect solar radiation emitted from the northern wall to enhance the thermal capacity of solar greenhouse dryers (Fig. 12). This is done by painting the northern wall with a reflective material (Berroug et al., 2011). Hartz et al. (1981) reduced the energy demand of a solar greenhouse by 14% when they fitted plywood painted with a white reflective coating material on the northern wall of a greenhouse. Sethi and Arora (2009) used an incline aluminized reflector sheet on the northern wall to reflect solar radiation transmitting out from the northern wall when the solar greenhouse was oriented in the east-west orientation. The dried product received the reflected beam radiation in addition to the solar radiation occurring from the horizontal plane which raised the product temperature. The use of a mirror by placing it on the northern wall has also been reported to reflect the beam radiation to the internal environment (Ahmad and Prakash, 2019; Berroug et al., 2011). However, Gupta and Tiwari (2005) stated that inclined reflective walls cannot minimize the solar radiation losses to zero.

5.2. Insulated opaque northern wall

The concept of insulating the northern wall has been presented in the literature to increase the temperature of a greenhouse when oriented in the east-west orientation. The method involves, either externally insulating the northern wall with an opaque material (Fig. 13) which is either black in color or the inside of the wall painted black to absorb heat energy which is released during the off-sunshine hours usually in the night (Selimefendigil et al., 2022). During the day the heat radiation trying to exit from the northern wall is stored by the black body which releases it during the night (Berroug et al., 2011). For a passive solar greenhouse, the thickness of the wall affects the optimal performance of the structure (Fang and Li, 2000). The external wall can be constructed with stones, board, polyethylene sheets (Santamouris et al., 1993), etc. Thus, this method has been used to improve the performance of greenhouse dryers by some researchers yielding 13.38~21.10% internal temperature enhancement for a natural convection solar greenhouse dryer (Chauhan and Kumar, 2016). Selimefendigil et al. (2022) in their method integrated an absorber coated with graphene nanoplatelet-embedded black paint into the north wall to serve as both opaque wall and heat storage materials. Their results showed a drying time reduction of 75~90 min compared to conventional greenhouses.

5.3. Sunken (earth-sheltering) northern wall

In some designs of the greenhouse, the north wall is formed by digging into the soil depth while the south wall and the roof form an arch resting on the northern sunken wall beneath the ground level as shown in Fig. 14. Digging the soil depth to form a north wall, also known as earth-sheltering or underground construction, offers superior thermal

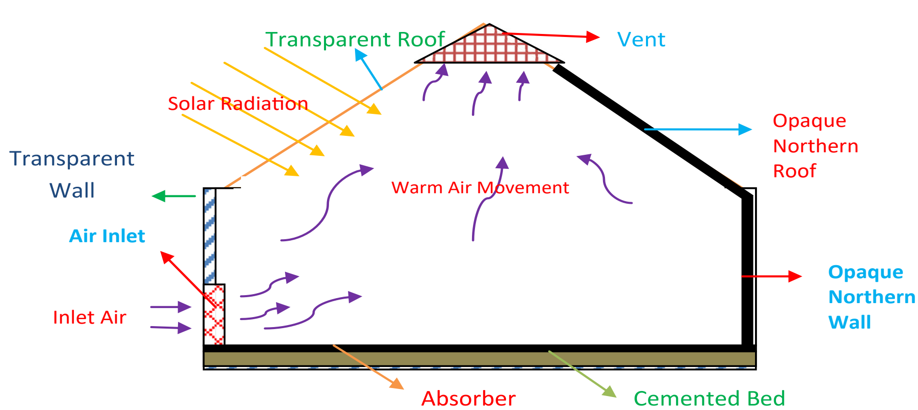

Fig. 13. Insulated Northern Opaque wall.

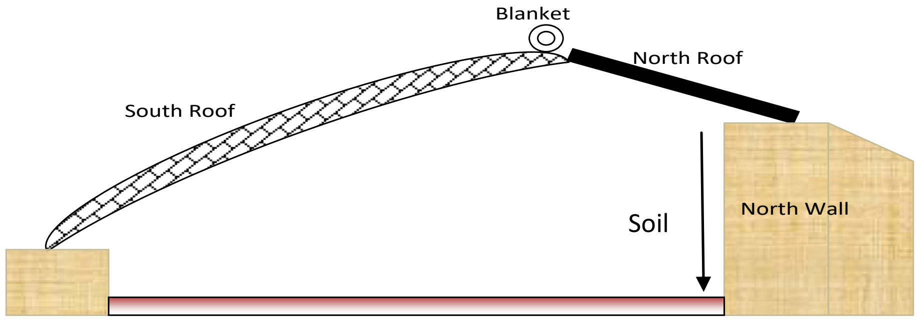

Fig. 14. Sunken northern wall greenhouse.

performance compared to other modification methods. By leveraging the natural insulation properties of soil, this approach provides higher thermal mass, reduced heat loss, and increased temperature stability (Cao et al., 2019). Compared to conventional insulation materials, earth-sheltering reduces thermal conductivity by 70~80% (Cao et al., 2019). Additionally, it eliminates the need for expensive insulation materials on the wall which can reduce the construction costs. However, it requires careful site selection and water management, earth-sheltering can enhance thermal efficiency, reduce energy consumption, and create a more sustainable and resilient greenhouse design, outperforming traditional northern wall modifications. This type of greenhouse is common in China and is used mainly for plant growth. The aim is to build a thicker northern wall and exploit the soil properties which include stable temperature, good heat absorption, and storage capacity (Cao et al., 2019). This structure can be adapted to low-temperature crop drying. However, in this design, optimal depth for optimum performance is a concern as increased depth beyond the optimal level can lead to, more shadow areas on the southern side that can lead to lower sun penetration (Cao et al., 2019). Additionally, it can lead to increased humidity which will be counterproductive to the drying process. To reduce moisture migration from the soil with the resultant effect on the humidity of the internal environment, the sunken wall can also be modified with bricks, marble, or concrete. However, increasing the depth of the sunken greenhouse produces better temperature uniformity within the internal environment (Cao et al., 2019).

5.4. Northern wall with heat storage materials

Several materials have been evaluated in solar thermal applications for their energy storage capacity (Ndukwu et al., 2017, 2020b, 2022d). These materials can be grouped into sensible and latent heat storage materials (Ndukwu et al., 2023b). Thus, these materials have been used to form the bricks of the northern wall in a solar greenhouse.

5.4.1. Sensible materials

Among the sensible materials used to modify the northern wall in the solar greenhouse are rock pebbles (Cao et al., 2019). Cao et al. (2019) also stated that pebbles have a good heat transfer coefficient, thus creating room for a fast heat transfer rate between the air and the pores. It allows the improved flow of warm air due to its arrangement that enhances wall porosity (Zhang et al., 2016). This leads to a higher temperature at night, especially during the winter which has been useful in crop drying. Therefore, the pebble has been used to form a heat storage northern wall (Fig. 15) or heat storage bed to improve thermal performance in solar greenhouse structures (Öztürk et al., 2003). Therefore, heat emitted from the southern wall during the day is absorbed by the pebbles installed at the northern wall as it tries to exit. During the night this heat is released for drying purposes. Other sensible materials that have been tested include perforated brick walls, common clay brick walls, and fine ash coal brick walls with the outer wall made of polystyrene board (Liu et al., 2019). However, fine ash coal brick walls demonstrated a better heat storage performance.

5.4.2. Latent or phase change northern wall

The major challenge of north wall adaptation in a greenhouse is that in most cases it is required to be very thick with a large floor area to improve the insulation capacity and the thermal performance. Thus, large materials are required which increases the cost with a lower heat storage capacity (Zhu et al., 2023). Thus, Zhu et al. (2023) stated that the use of latent heat or phase change material (PCM) can overcome the above problem. Phase Change Materials (PCMs) are substances that absorb and release thermal energy as they change phase from liquid to solid or vice versa, maintaining a stable temperature (Ndukwu et al., 2017). These material evolve a large amount of latent heat as it changes from liquid (after melting from absorbed solar heat) back to solid (as it loses the absorbed heat during the cold periods) over a narrow range of

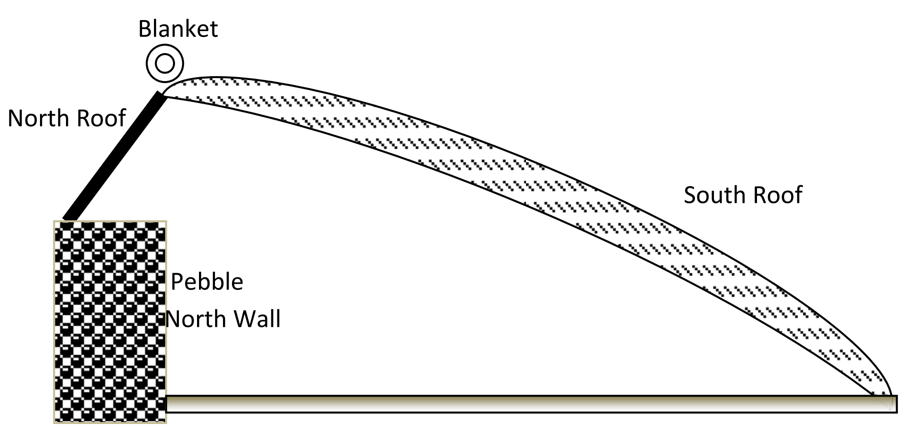

Fig. 15. Pebble heat storage northern wall.

temperature difference. In greenhouses theses materials are integrated into the northern wall to enhance thermal efficiency by:

- ➢ Absorbing excess heat during the day, reducing temperature fluctuations
- ➢ Releasing the stored heat at night, maintaining optimal temperatures
- ➢ Providing thermal mass without the need for large amounts of conventional heat storage materials
- ➢ Regulating temperature extremes.

Therefore, these materials have found a wide range of applications in forming part of the northern wall for a solar greenhouse (Singh and Tiwari, 2000). Some of these phase change materials include fatty acids, $Na_2\ HPO_4{\cdot}12H_2O$, sodium sulfate Decahydrates, Glauber salt, glycerine, paraffin, etc. Integrating PCMs into greenhouse design, such as in walls, roofs, or storage systems, can improve thermal efficiency, reduce energy consumption, and create a more stable and optimal growing environment. These materials were either encapsulated, embedded into bricks, or boards placed on the northern wall (Boulard et al., 1990). With the use of PCM, the temperature of the greenhouse can be raised to 4.2°C (Cao et al., 2019). The integration of PCM into the northern wall can be by passive means (Santamouris et al., 1994; Chen et al., 2018) where the wall is charged by natural convection power by the solar radiation heat directly or by active means where the PCM northern wall is charged through a link to an external solar collector or a heat exchanger.

5.5. Modified or variable south roof with modified north wall

To achieve optimum performance from a greenhouse dryer, some researchers combined modification of the south roof with that of the northern wall (Cao et al., 2017). A variable southern roof, combined with a modified northern wall, optimizes solar greenhouse performance by dynamically controlling solar radiation intake, ventilation, and insulation. The variable roof adjusts to regulate heat gain, while the modified northern wall enhances thermal mass, natural lighting, and insulation. This synergy balances solar radiation distribution, reduces temperature fluctuations, and improves microclimate control. The integrated system reduces energy consumption, and enhances thermal performance. By adapting to changing environmental conditions, the variable southern roof and modified northern wall creates optimum operating conditions for the solar greenhouse. Solar radiation intensity that enters the greenhouse in the northern hemisphere is a function of the angle of the south roof. A smaller angle of the southern roof leads to higher beam reflection that limits solar radiation penetration into the greenhouse (Cao et al., 2019). Therefore, the south roof angle should be reasonably high enough to the horizontal plane to meet the roof facing the south and the projection angle of the solar radiation at mid-day (Cao et al., 2017). This angle can be determined according to Sethi and Dubey (2011) as follows:

$$\alpha_s = sin^{-1}(sin\delta\ sin\varnothing + cos\delta\ cos\varnothing\ cos\omega) \quad (1)$$

Where:

$\varnothing$ is the north latitude of the location in degrees

ω is the hour angle in degrees given as → 15 (t_{solar} – 12), t_{solar} is the solar time of the day

δ is the Declination angle of the sun given as →23.45 × sin [360 (284 + n)/365].

Thus, the modified northern wall can absorb large amounts of solar radiation emitted from the southern roof. Hence, as the solar altitude varies during the day it affects the sunlight ray passing into the greenhouse. To overcome this, a variable roof that responds to variations in solar attitude has been designed with a modified northern wall for higher thermal performance in China (Zhang et al., 2014). Cao et al. (2017) reported a temperature increase of 2.9~4.3°C on the variable southern roof compared to the fixed southern roof which can be effective in low-temperature drying. Apart from the variable south roof, it is believed that during the off-sunshine periods, when the modified northern wall starts to release its heat, the southern roof becomes a conduit for heat losses. Thus, researchers have used different kinds of materials such as non-woven and sprayed cotton to insulate the southern roof during the off–sunshine periods especially in the night to retain the heat released from the northern wall (Liu et al., 2019).

6. Research on modification of the northern wall of the greenhouse dryer

The various designs and modifications of the greenhouse have been adopted to dry various crops in various countries. The reason is that solar greenhouse offers an opportunity for large-scale low-temperature drying. Thus, a solar greenhouse with an insulated opaque north wall and a solar collector was presented by Chauhan and Kumer (2016). The modified greenhouse solar dryer tested under no load condition showed an increase in the convective heat transfer coefficient (29.094 $W/m^{2\circ}C$) by the insulated opaque north wall compared to the greenhouse with only an additional solar collector. This shows the effectiveness in heat utilization and lower heat loss as shown in the calculated heat loss factor. Hence it consistently maintained a higher room temperature compared to the un-insulated northern wall type.

Drying of onions in India was carried with a modified northern brick wall with an inside surface painted black for an even-span solar greenhouse (Jain, 2005). The bed of the greenhouse was also packed with a rock bed to assist in the drying process. Although a comparison was not made with the non-insulated northern wall, the transient study of the drying parameters in terms of geometric dimensions showed that with a drying rate of 0.278 kg/s, the dryer can effectively dry 2280 kg of onions under 24 h. Sethi and Arora (2009) used an inclined aluminized reflector sheet in the northern wall to enhance the optimum performance of a greenhouse dryer. The aim is to combine the direct incident radiation energy and reflective beam energy to cause a higher thermal effect on the dried product. Thus, increasing the temperature and the drying rate of the product. Under passive mode, this modification reduced the drying time by 13%, but the effect increased when the drying was done in active mode as the crop temperature increased compared to the increase in the passive mode with a time saving of about 16.6%.

Another solar greenhouse dryer with an insulated opaque northern wall was tested in India under no load conditions (Prakash and Kumar, 2014). The solar dryer was tested with or without a concrete bed. Parameters such as instantaneous efficiency loss factor, convective heat transfer coefficient, ventilation rate, and number of exchanges per hour were investigated. Using the insulated opaque north wall minimized the heat loss from the dryer. Selimefendigil et al. (2022) presented two modified greenhouse dryers for drying Granny Smith apples in Turkey. In the first case, the northern wall was insulated with an opaque aluminum sheet north wall while in the second case, the northern insulated wall was integrated with Graphene nanoplatelets coated with matt black paints. Both designs were thermally assessed to compare their performance with the conventional solar greenhouse dryer. The insulated north wall modification resulted in an exergy efficiency of 4.67~5.38% compared to 2.61~2.70% for the conventional greenhouse with a time reduction of 75~90 min.

A parabolic and triangular solar greenhouse dryer with the north wall internally insulated with glass wool while the external wall was covered with plywood were comparatively investigated for their thermal performance when the solar radiation intensity ranged from 1000 to 1183 W/m^2 (Purusothaman and Valarmathi, 2021). Although the northern wall insulation enhanced the performance of the solar greenhouse compared to the conventional one the overall performance of the parabolic-shaped greenhouse was better. Ahmad and Prakash (2019) compared the performance of an even-span greenhouse solar dryer with the north wall insulated with a reflective opaque mirror under different bed conditions. The bed condition includes ground floor, concrete floor, gravel floor, and black painted gravel floor. However, the result analysis showed that black painted gravel floor with an insulated reflective opaque mirror northern wall performed best but the entire thermal; parameters considered were better than conventional type solar greenhouse.

Chauhan and Kumar (2018) presented thermal modeling of drying gooseberry using a solar greenhouse with an insulated north wall stainless steel reflector under active and passive modes. They developed an empirical model to simulate the surface evaporation rate of the gooseberry. They concluded that under the operating conditions, their model performed better, however, other performance indices showed that the passive greenhouse solar dryer with the insulated opaque north wall is the most effective. The same dryer was used to dry bitter guard and the thermo-environmental analysis was carried out in Thailand (Chauhan et al., 2018). The logarithmic model was the best-selected model to predict the moisture ratio of the bitter guard in this dryer however the payback period of the passive operational mode was lower than the active mode and was given as 1.63 years.

Rathore and Panwar (2010) investigated a 37.5 m^2 (drying area) hemi cylindrical solar greenhouse dryer in India for drying 320 kg of seedless grapes. Providing a drying efficiency of 30%, the solar dryer dried the untreated grapes from 85% moisture content to 16% in 7 days. However, a comparison was not made with non-insulated walls. The same dryer was used by Sevda and, Rathore (2010) to dry 810 kg of handmade paper using a floor drying area of 122.95 m^2. They concluded that the performance of the solar greenhouse dryer is satisfactory having provided a temperature range of 18~22°C above the ambient and can be adopted in industrial scale operation. Panwar et al. (2013) presented experimental and thermal modeling of the same semi-cylindrical dryer mentioned above. In their study, they used the solar greenhouse dryer to dry 600 kg of surgical cotton with a moisture content of 40%~5% in a day. The study used energy and mass balancing on various components and fluid flow to predict the temperature of the drying chamber. The obtained modeling results were 2~3°C above the drying chamber temperature which is a good result. Table 1 summarises the performance of these dryers with inferred conclusions while Table 2 shows the floor areas and the cladding materials used.

7. Performance indicator for the modified northern wall of the greenhouse dryer

The common indicators similar to conventional solar dryers like drying rate, specific energy consumption, specific moisture extraction rate, drying efficiency, exergy efficiency, greenhouse gas emission, cost analysis, drying time, and quality of the dried product (Selimefendigil et al., 2022) has been used in the evaluation of solar greenhouse dryers with modified northern wall. However, to evaluate their performance and compare them quantitatively with other conventional solar greenhouse dryers the key indicators are shown in Table 3. This includes heat utilization factor (HUF) which is the ratio of the difference between the bed and room temperature and the bed and ambient temperature (Ahmad and Prakash, 2019). It represents the degree of temperature reduction due to air cooling during drying (Tiwari, 2009). This is similar to the coefficient of performance (COP) however, the difference is that COP is the ratio of temperature difference between the drying chamber and ambient and the bed temperature and ambient temperature (Tiwari, 2009). The instantaneous thermal loss factor (η_{th}) at the product top envelops and at the vent is also determined as an evaluation index because the ratio of these products gives the coefficient of diffusion (C_d) from the dried product which is the major driving force in solar greenhouse dryer (Chauhan and Kumar, 2016). Furthermore, the Heat loss factor (HLF) results from much air which is in excess moving part of the heat towards the ventilator or the roof (Chauhan and Kumar, 2016). This factor is also another index common to greenhouse evaluation research. This occurs if the air has low density. The convective heat transfer coefficient (h_{ct}) is an indicator for the rate of heat loss from the drying chamber to the surroundings (Singh and Kumar, 2012) and has also formed part of evaluation indices for solar greenhouse dryers.

8. Industrial scalability of the developed solar greenhouse with the modified northern wall

The challenge of most developed greenhouse dryers just like many drying equipment developed at the laboratory scale is the industrial scalability of the dryers. With good quality of solar dried products, a scalable industrial solar greenhouse with a modified northern wall will have less environmental impact compared to other existing industrial dryers. Scalability of dryers is the ability to obtain the same results when a large product on an industrial scale is dried with similar efficiency. It can be quantified as the total amount of dried product (m_d) divided by the total drying time (t_d) dissipated in drying the product (m_d/t_d). There is growing interest in adopting renewable energy-based dryers especially solar dryers irrespective of design. However, the challenge is up-scaling the developed dryers to industrial systems. One of the hurdles is achieving uniformity in the drying of products. Irrespective of the design of the solar dryer the heat transfer fluid moves from the crop closer to the inlet across crop layers either horizontally or vertically before exiting. This will lead to possible successive saturation of the heat transfer fluid, thus diminishing the moisture-carrying capacity of the air downstream. This becomes more pronounced when multiple trays are used at various distances from the inlet. Thus, developing a solar greenhouse capable of uniform moisture-dried products is important. The use of rotary trays, and intermittent mixing of dried product and trays is a possibility in design. Most modified northern wall greenhouse dryers are passive dryers, and thus might not result in a shorter drying time when compared to other industrial dryers. The passive design of most solar greenhouses might be a result of the operational environment where the user's (farmer) income is considered on its affordability. This poses a challenge and some serious questions when a product needs to dry faster like in the industrial setting. Two solutions can be suggested which include active heating with an evacuated tube collector is a suggested alternative to assist passive solar greenhouse dryers. Currently, wind-powered solar greenhouses are in existence to reduce the cost of powering the greenhouse in active air convection mode and can also help in upscaling the existing solar greenhouse dryers irrespective of design.

In the absence of effective solutions, particularly during Northern Hemisphere winter seasons, scalable industrial solar greenhouses with modified northern walls emerge as a promising alternative. Deploying scalable industrial solar greenhouses with modified northern walls offers numerous environmental benefits. These greenhouses provide superior thermal efficiency and energy savings compared to traditional transparent greenhouses, particularly during winter periods. By reducing heat loss and optimizing natural lighting, they decrease energy consumption. Notably, research by Anuma et al. (2024) reveals that greenhouses with opaque northern walls exhibit higher exergy efficiency, leading to enhanced environmental sustainability. This is attributed to lower waste exergy, which, as Dincer and Rosen (2013) highlight, can disrupt environmental equilibrium by re-radiating solar energy. The reduced exergy waste in solar greenhouses with modified northern walls supports climate change mitigation and lowers greenhouse gas emissions. Furthermore, farmers and industrial food producers will benefit from:

- Faster drying times, reducing crop processing periods
- Year-round food production, increasing yields and returns
- Extended growing seasons, enabling multiple harvests annually

These advantages make industrial solar greenhouses with modified northern walls a more sustainable, energy-efficient, and profitable solution for farmers, contributing to a more environmentally resilient food system.

Table 1
Research and results in modified solar greenhouse north wall.

Shape	Orientation	Modification type	Parameters investigated	Crop dried	Conclusion	Reference
Even Span	East-West Orientation	Insulated opaque north wall	Heat transfer coefficient, room temperature, heat utilization	–	The insulated opaque north wall improved the heat utilization and temperature of the room by 4.11~11.61% compared to transperent green house	Chauhan and Kumer (2016), 2017
Even span	East-West Orientation	Brick northern wall	Effect of length and breadth of greenhouse and mass flow rate of air on the temperatures of crop	onions	Thermal loss was reduced by the brick wall, thus improving the drying rate of onions	Jain (2005)
Conventional greenhouse	East-West Orientation	Inclined reflective northern wall	Optimum width of tray, drying time	bitter gourd	The optimum solar radiation energy in terms of the width of trays was selected and drying time was determined.	Sethi and Arora (2009)
Even span	East-West Orientation	Insulated opaque north wall with inclined mirror	instantaneous efficiency loss factor, convective heat transfer coefficient, ventilation rate, and number of exchanges per hour	–	Modification of the north wall minimized the heat loss from the dryer	Prakash and Kumar (2014)
Single slope	–	Insulated opaque north wall and Graphene nanoplatelets coated with matt black paint north wall	Exergy efficiency, drying time, drying rate, and specific energy consumption	Granny Smith apples	Exergy efficiency was higher, with a shorter drying time and a lower specific energy consumption	Selimefendigil et al. (2022)
Parabolic and triangular	–	Insulated opaque north wall with plywood outside and Glass wool covered with aluminum foil inside as reflective material	Product temperature, energy level, and proximate food composition of dried product	grape	The northern wall insulation enhanced the performance of the solar greenhouse compared to the conventional one but the overall performance of the parabolic-shaped greenhouse was better	Purusothaman and Valarmathi (2021)
Even span	East-west	Insulated reflective opaque mirror north wall	Coefficient of diffusivity, heat loss factor, heat utilization factor, heat transfer coefficient	–	black painted gravel floor with insulated reflective opaque mirror northern wall performed best but the entire thermal; parameters considered were better than conventional type solar greenhouse	Ahmad and Prakash (2019)
Even span	East-west	Insulated polystyrene sheet opaque north wall with stainless steel reflector	Thermal modeling of evaporation rate and study of drying kinetics	Gooseberry	The insulated thermal wall reduced the heat loss and improved the solar dryer performance	Chauhan and Kumar (2018)
Even span	East-west	Insulated polystyrene sheet opaque north wall with stainless steel reflector	Thermal modeling of evaporation rate and study of drying	Bitter guard	The insulated thermal wall reduced the heat loss and improved the solar dryer performance	Chauhan et al. (2018)
Semi-cylindrical	–	Insulated north wall	Temperature behavior and drying time	Seedless grapes	The solar dryer produced a drying efficiency of 30%	Rathore and Panwar (2010)
Semi-cylindrical	–	Insulated north wall	Drying kinetics and economic analysis	paper	Dried handmade paper in 4~5h from a moisture content of 53.85% ~9.96%	Sevda and, Rathore (2010)
Semi-cylindrical	–	Insulated north wall	Energy and exergy efficiency, economic analysis, and carbon mitigation potentials were studied	Surgical cotton	Moisture content was reduced from 40% to 5% in a day. Thermal predictions of the temperature of the drying chamber obtained modeling results of 2~3°C above the drying chamber temperature	Panwar et al. (2013)

Table 2
Geometric dimensions and cladding materials.

Ref.	Floor Area of greenhouse	Greenhouse type	Modification of the north wall	Cladding material
Prakash and Kumar (2014)	1.5m^2	Active even span roof type	Inclined mirror on the insulated north wall	
Selimefendigil et al. (2022)	0.313m^2	Single slope	Insulated opaque north wall and Graphene nanoplatelets coated with matt black paint north wall	polyethylene
Chauhan and Kumar (2018)	1.5m^2	Active even span roof type	Insulated opaque north wall	UV-treated polycarbonate sheet
Purusothaman and Valarmathi (2021)	–	parabolic shape	Insulated opaque north wall with reflective material	PVC sheet
Ahmad and Prakash (2019)	1.5m^2	even span roof type	Insulated opaque north wall	UV-treated 1 mm thick acrylic sheet cover
Sethi and Arora (2009)	24 m^2	even span type	inclined reflecting north wall	UV-stabilized polyethylene sheet
Rathore and Panwar (2010)	37.4 m^2	semi-cylindrical	Insulated opaque north wall	UV stabilized polyethylene sheet
Sevda and, Rathore (2010)	122.95 m^2	semi-cylindrical	Insulated opaque north wall	UV stabilized polyethylene sheet

Table 3
Key performances Indices for modified northern wall solar greenhouse dryers.

Indices	Formula	Source
HUF	$\frac{T_{bed}-T_{room}}{T_{bed}-T_a}$	Chauhan and Kumar, 2016
COP	$\frac{T_{bed}-T_{room}}{T_{bed}-T_a}$	Chauhan and Kumar, 2016
η_{th}	$\frac{U\sum A_i(T_{room}-T_a)}{I_{gr}A_c}$	Chauhan and Kumar, 2016
C_d	$\frac{(1-\eta_{th})I_{gr}A_c}{\left(\eta A_{vent}\left(\frac{2\Delta P}{\rho}\right)^{1/2}\times VP\right)}$	Ahmad and Prakash, 2019
HLF	$C_d\times A_{vent}\left(\frac{2\Delta P}{\rho}\right)^{1/2}\times VP$	Ahmad and Prakash, 2019
h_{ct}	$0.884\left[(T_{bed}-T_{room})+\frac{[P(T_{bed})-Rh_aP(T_{room})](T_{room}+273)}{268900-P(T_{bed})}\right]^{1/3}$	Chauhan and Kumar, 2016

9. Conclusion

This article provides an overview of a solar greenhouse dryer with a modified northern wall. To improve the thermal performance of solar greenhouses either for crop growth or drying, several modification approaches have been adopted. This article therefore highlights various modification methods adopted to improve the thermal performance of the greenhouse with a focus on the northern wall. Efforts were mainly focused on the northern wall because it can be a conduit for heat loss if not modified during the cold period. The various strategies adopted in the modification of the north wall structure include creating an opaque north wall, installing a reflective north wall, using heat storage materials like pebbles or brick, integrating phase change materials into the north wall, digging the soil depth to form a north wall and creating a variable southern roof with a modified north wall. Modifying the northern wall showed higher drying chamber temperature compared to completely transparent convectional greenhouse dryers in all the studies. With this approach, the energy management system of the greenhouse can be optimized for higher performance making it more sustainable and eliminating the use of fossil fuel in agricultural product drying. Greater deployment of even span greenhouse dryer with insulated northern wall was noticed and the passive solar greenhouse performance can be improved greatly by modifying the northern wall. With a good quality of solar dried product, a scalable industrial solar greenhouse with a modified northern wall will have less environmental impact compared to other existing industrial dryers.

CRediT authorship contribution statement

M.C. Ndukwu: Writing – review & editing, Writing – original draft, Visualization, Supervision, Software, Resources, Project administration, Methodology, Data curation, Conceptualization. **Leonard Akuwueke:** Resources, Visualization. **Godwin Akpan:** Writing – review & editing. **M.F. Umunna:** Resources, Visualization. **Godwin Usoh:** Resources, Visualization. **Inemesit Ekop:** Writing – review & editing. **Promise Etim:** Visualization. **I. Okosa:** Writing – review & editing. **Francis Orji:** Resources, Visualization. **E.C. Ikechukwu-Edeh:** Writing – review & editing. **Ifiok Ekop:** Writing – review & editing. **Merlin Simo-Tagne:** Visualization. **Lyes Bennamoun:** Writing – review & editing. **Hongwei Wu:** Visualization. **Fidelis Abam:** Writing – review & editing, Formal analysis, Data curation.

Declaration of competing interest

We the authors declare no conflict of interest whatsoever. The authors agreed to submit this article to GERS.

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