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Cellulose Nanofiber aerogel as a potential receiver layer for solar application: A review

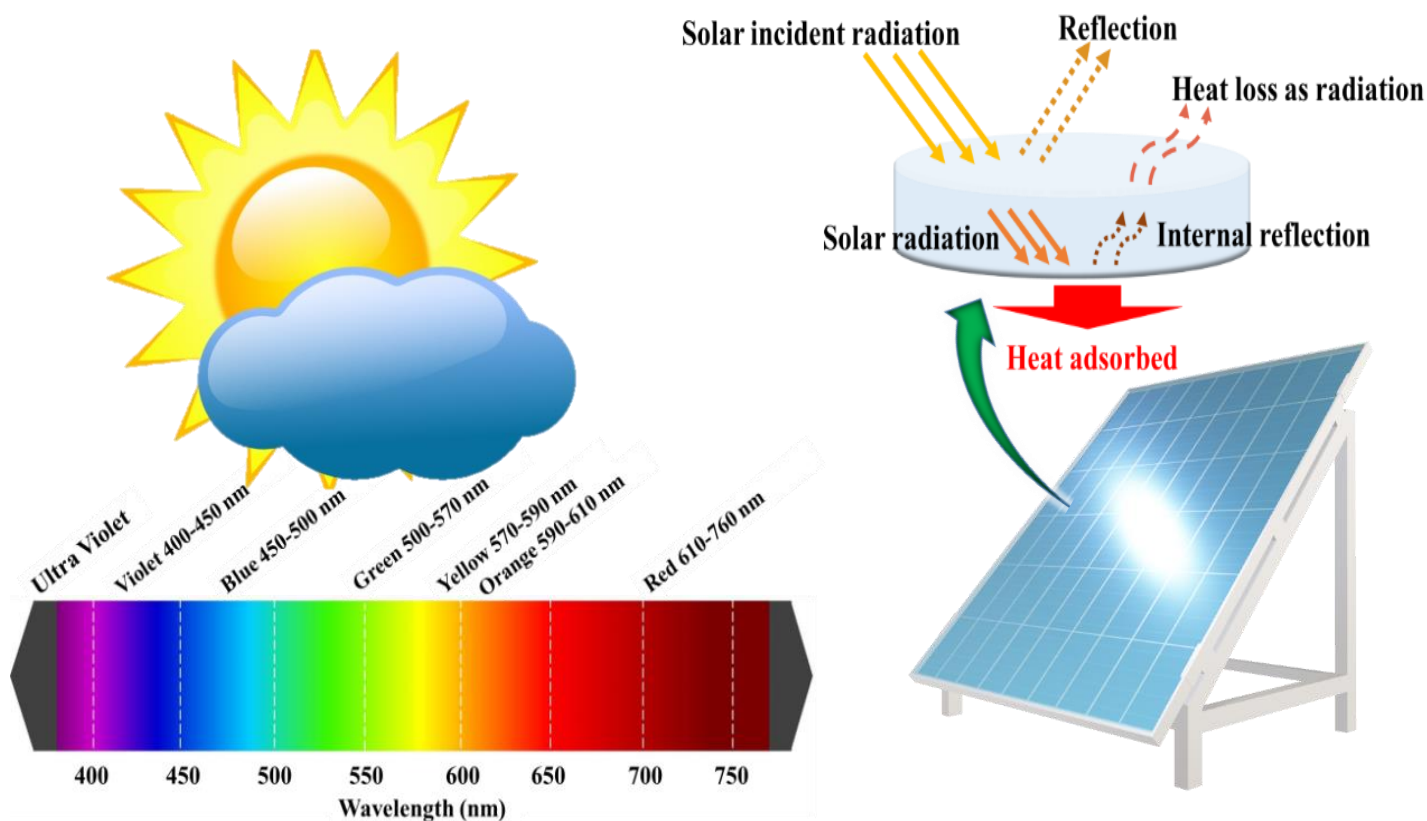
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Graphical abstract



Abstract

The population explosion, industrialization, and technological advancements have resulted in fast-growing energy demand around the world. Hence, there is a requirement for reliable and sustainable energy for addressing the long-term energy crisis. In this context, solar energy-based developments are gaining traction steadily all over the world owing to the ever-increasing energy demands while conventional energy sources are depleting and often used as geopolitical tools. To maximize the growth potential and identify the increasing concerns regarding sustainability, different materials have been developing around the world. Nanocellulose is a biomass-derived emerging material consisting of cellulose fibrils having a width in the order of the nanometer range (i.e., 2–100 nm) that can also form complex structures like aerogels. The nanocellulose aerogels combine intriguing interconnected three-dimensional porous characteristics of aerogel-type materials such as high porosity, large surface area, and low density. This paper discusses the different fundamental concepts of solar energy generation using nanocellulose aerogels. Moreover, the key properties of cellulose nanofiber aerogel in the solar thermal technology applications such as high porosity, mechanical strength, thermal stability, optical properties, and thermal conductivities were discussed in detail. This contribution also introduces different articles published in recent years about nanocellulose-based porous materials in the fields of solar thermal technology and their future.

Abbreviations: **CSP**, Concentrated solar power; **PV**, Photovoltaic; **PT**, Photothermal; **PVT**, Photovoltaic- thermal; **CNF**, Cellulose nanofiber; **PTR**, Parabolic trough receiver; **CRS**, Central receiver system; **PPI**, Pores per inch; **CMP**, Conjugated micro porous polymer; **SHGC**, Solar heat gain coefficient; **TSET**, Total solar energy transmittance; **CNC**, Cellulose nanocrystal; **BC**, Bacterial cellulose; **CBCA**, Cellulose based carbon scaffold; **AMIMCl**, 1-allyl-3-methylimidazolium chloride; **GO**, Graphene oxide.

1. Introduction

Solar energy, as a clean and inexhaustible energy source, if harvested efficiently, could potentially relieve human beings from the global energy crisis. This can also reduce the environmental deterioration caused by the overreliance on fossil fuels. Aiming at efficient utilization, persistent endeavours have been devoted to harvesting and converting solar energy into varied forms of energy. This includes electrical energy via solar photovoltaics [1], concentrated solar thermoelectrics [2], chemical energy via photocatalysis [3], photo electrolysis, and thermal energy via the solar steam process [4]. Fig. 1 illustrates some of the major solar applications that are used across the sector and the year in which they have developed. Among these solar-energy utilization approaches, light-to-heat conversion by a heat localizing layer with excellent visible and near-infrared light absorbing capacity has been demonstrated to be extremely efficient, showing solar thermal conversion efficiency as high as 90% [5]. Concentrated solar power (CSP) systems employ large concentrating optics to focus sunlight onto an absorbing receiver which then transmits heat at high temperatures to a working fluid for direct use or electricity generation via a heat engine. Solar radiation is absorbed as heat by a receiver, either in the form of an absorbing surface, a receiver cavity, or a volumetric absorber. The non-concentrating solar collectors are short as low operating temperature ranges that severely limit their applications [6]. CSP systems have the advantage of being cheap, efficient and high thermal dispatch ability storage to supply energy over a 24-hour output cycle [7]. It is known that the receiver efficiency directly influences the plant efficiency, and a 1% improved receiver efficiency can improve the plant efficiency by 0.9–1.4%. Therefore, improving the receiver efficiency by reducing heat loss has become an important topic for improving overall plant efficiency. Many techniques have been proposed to reduce heat loss from the receiver. These techniques could be divided into two approaches that are enhancing the heat transfer inside the absorber and reducing the heat loss at the absorber outside [8].

Maximizing efficiency is one of the most important challenges dictating the success of any renewable energy technology and it is largely dependent on the structure and properties of candidate materials [9].

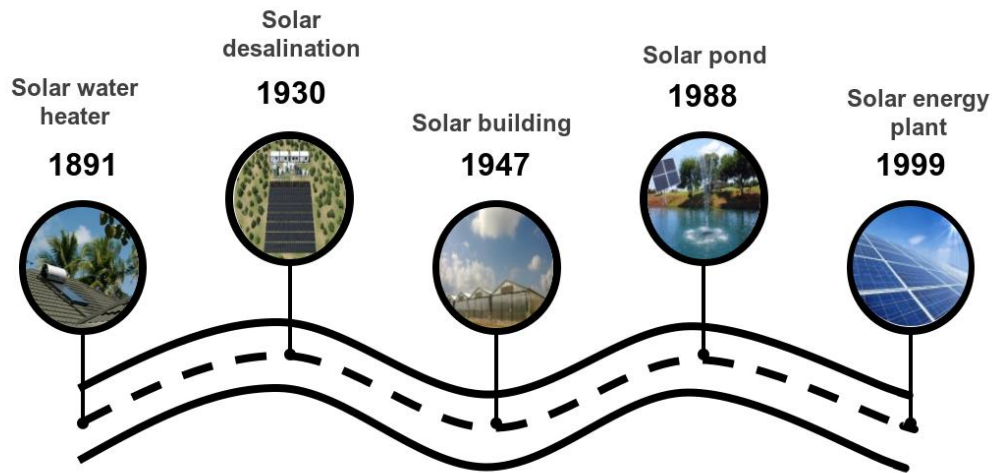


Fig. 1. Current solar thermal applications and each as a function of year.

A comparison of solar energy production worldwide between 2010 and 2021 from the International Renewable Energy Agency (IRENA) presented in Fig.2(a) demonstrates a clear increment in global energy production using solar technology. Fig.2(b). illustrates how much percentage of the total energy produced by different countries and continents is from solar energy. Asia produces the highest percentage of solar-based energy (28%) in comparison to Europe which produces 14% of energy from solar-based technology. Among the emerging Asian countries, India and China produced 6.5% and 6.2% respectively. Fig.2 (c) compares the total percentage of energy produced from solar technology between 2010 and 2021 by different countries and continents. Countries like India, China, and France have 68%, 32%, and 15% increments whereas Asia and Europe have 327% and 587% increments in solar-based energy production. Moreover, during the same time frame, solar-based energy production increased by 2945% worldwide [10]. As of 2021, solar-based energy production has reached 28% of all the

energy produced around the world. Solar thermal technology for various industrial heat applications is briefed in Table 1 [11].

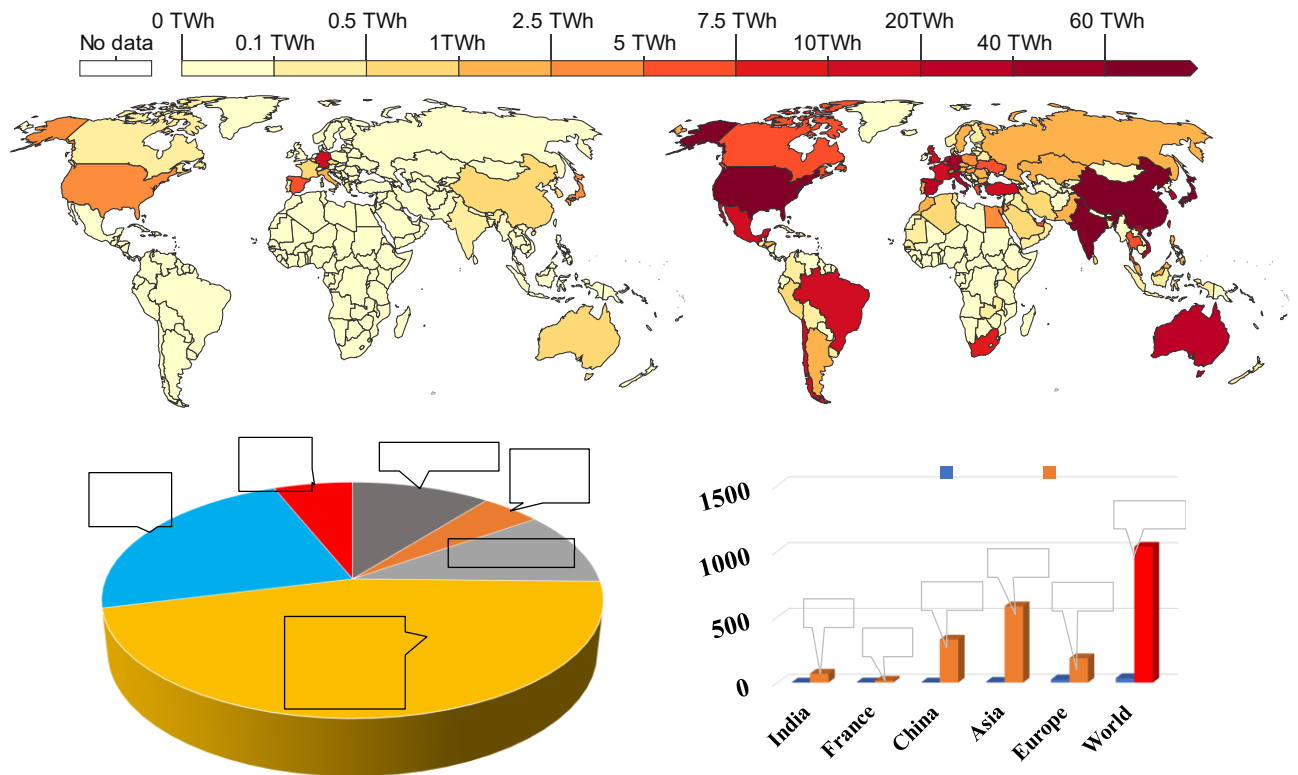


Fig. 2. Global solar energy production between (a) 2010 and 2021. (b) Percentage of solar energy produced by different countries, continents, and the world (c) Comparison of total solar energy produced by different countries between 2010 and 2021 with increment in percentage. Data were taken from International Renewable Energy Agency[12].

Industrial application	Technology	Type of system
Solar water heater	• Thermosyphon systems	Passive
	• Direct circulation	Active
	• Indirect water heating systems	Active
Solar desalination	• Solar stills	Passive
	• Multistage flash	Active
	• Vapour compression	Active
Space heating and cooling	• Space heating and service hot water	Active
	• Air systems	Active
	• Heat pump systems	Active
	• Absorption systems	Active
Solar thermal power generation	• Parabolic trough collector systems	Active
	• Parabolic tower systems	Active
	• Parabolic dish systems	Active
	• Solar furnaces	Active

Table 1 Solar industrial applications & technology used [11].

The advancement in nanomaterials promotes the performance of solar technology almost in all cases; photovoltaic (PV), photothermal (PT), and photovoltaic-thermal (PVT). The porous media which processes a complex three-dimensional geometry allow the solar radiation to penetrate the structure and be gradually absorbed. Porous materials, particularly aerogels, are widely discussed in the literature concerning insulating and preserving energy [13]. This is visible in the increasing number of articles published and patents over the period 2011 to 2020 as depicted in Fig. 3. and Fig. 4. Porous materials such as aerogels are characterized by their low density, large porosity (>99%), high specific surface area, low thermal and electric conductivity. Owing to these unique and useful properties, aerogels are widely employed in the manufacturing process. [14]. Inorganic, organic, and carbon are the three classifications of aerogels. Various inorganic materials including silica, clay, and certain metals such as Cr and Fe are used to fabricate aerogels. Nevertheless, the negative aspects of these kinds of aerogel are the exploitation of non-renewable sources and solid waste generation. Silica aerogels are exciting, but due to their extreme fragility and inherent hydrophilia, they have weak mechanical

properties and a limited range of applications [15]. To combat the aforementioned shortcomings of silica-based aerogels, organic aerogels such as polymer-based aerogels (such as polyimide, poly(vinyl alcohol), polyurea, resorcinol-formaldehyde, and melamine-formaldehyde) and bio-based aerogels (such as cellulose, starch, and pectin) have been created. Studies have reported that, owing to the specific characteristics of the organic fibres, it can improve the mechanical strength and modulus of the aerogels. This enables the aerogels synthesized with organic fibres to be employed in a wider application spectrum [16]. However, the aerogel synthesized by organic fibres has certain disadvantages like high operation costs derived from the complicated apparatus and precursors used. The overall higher time consumption also contributed to an expensive preparation process. These problems can be addressed by preparing 1-dimensional nanofibrous polymeric aerogel and composites. This polymeric aerogel can form a chemically cross-linked 3D network or physical interlinking that is derived from the nano-fibrillar structure. This added flexibility in comparison with the interconnected solid frameworks formed by inorganic aerogels reduces the stress concentration in the whole 3D network within the aerogel microstructures.[17].

Issues such as greenhouse gas emissions, embodied energy, toxicity, and the sustainability of materials are becoming increasingly significant to society. To minimize the environmental impacts and to create a sustainable future, low-cost and energy-efficient carbon-based green materials are being increasingly explored as candidates to replace conventional materials in the fabrication of energy devices. Our desire for sustainable development is motivated by our understanding of the need to protect nonrenewable resource depletion. One of the most important classes of carbon-based materials made from natural resources is cellulose. Relative to inorganic aerogels, cellulose aerogels are generally less brittle, even flexible, and easily compressed to a larger strain of more than 50% without disintegration, especially for the nanocellulose aerogels consisting of native cellulose I crystals with very high modulus and

strength. The properties listed above make nanocellulose particularly suitable for the development of lightweight porous materials. Cellulose nanofibers (CNF) can be synthesized from various raw materials like; wood, natural fibres, and non-processed and processed waste from agricultural and industrial residues that mainly contain lignocellulosic biomass. Various pre-treatment processes like enzymatic, chemical, or ionic-liquid can be applied for the extraction of cellulose from cellulosic biomass. In addition, several mechanical treatments such as high-pressure homogenization, ultra-sonication, or cryo-crushing techniques can be applied to fibrillate the pre-treated cellulose into nano-dimensional cellulosic fibres. From the environmental point of view, nano-fibrillated cellulose aerogel would be a promising candidate to replace inorganic and petroleum-based aerogel. The reasoning behind the advantages gained by flexible nanocellulose-based aerogel over the brittle silica-based aerogel counterparts is beyond the inherent physical and chemical properties, sustainability, and renewability, it is because of the physical dissolution and regeneration technique from non-derivatizing cellulose solvents is simple, “green”, easy for industrialization that possessing great potentials [18]

The scope of the article is to explore the current studies that investigate the use of cellulose aerogels in solar applications that potentially would impact day-to-day life. This review will provide an in-depth understanding of cellulose nanofiber aerogel-based materials as they apply to solar thermal technology. The summary of this section is schematically represented in Fig 5. The nanocellulose based can be utilized in concentrating optics devices to replace conventional non-sustainable material as well as enhancing their performances.

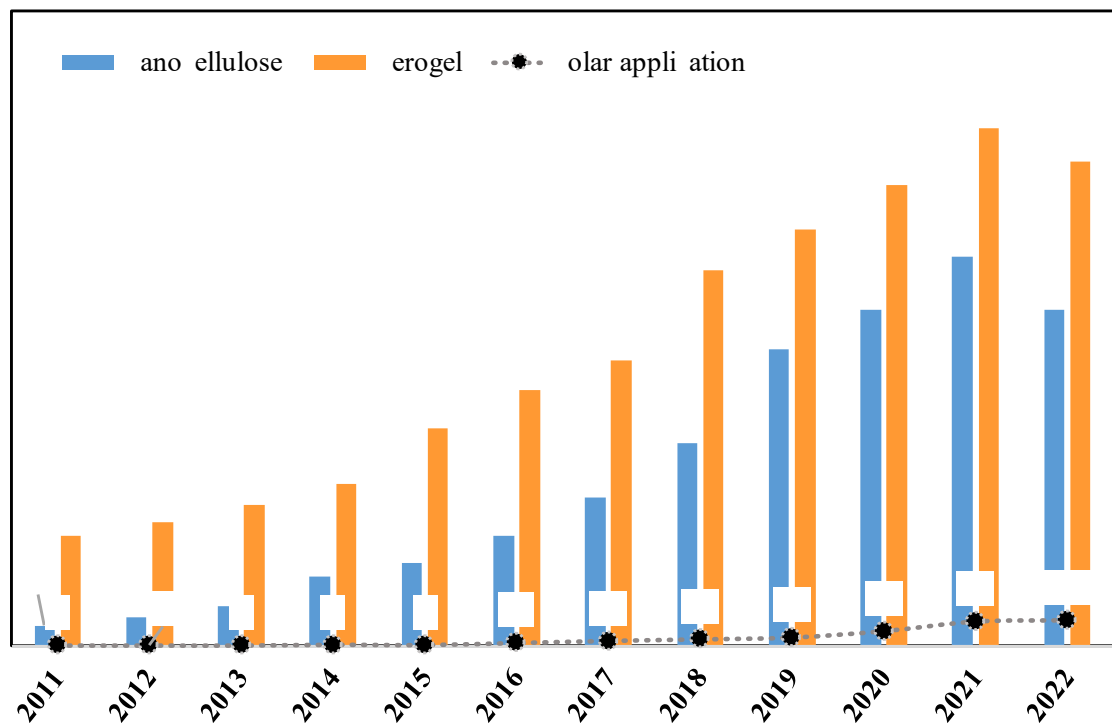


Fig. 3. Number of scientific articles published in nanocellulose (blue bar), aerogel (orange bar) and nanocellulose based aerogel in solar application (Source: scopus)

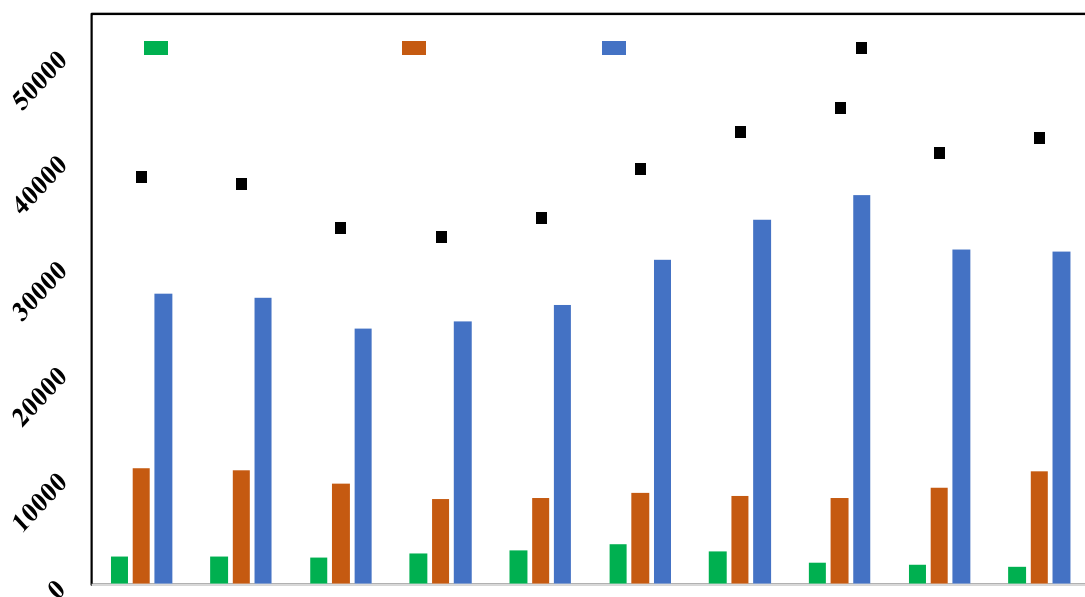


Fig. 4. Number of patents published on different solar technologies: PV-thermal hybrids (green bar), solar thermal (maroon) and solar photovoltaic (blue bar) and total patents (black squares) between 2011 and 2020 (Source: Patents Evolution (irena.org)).

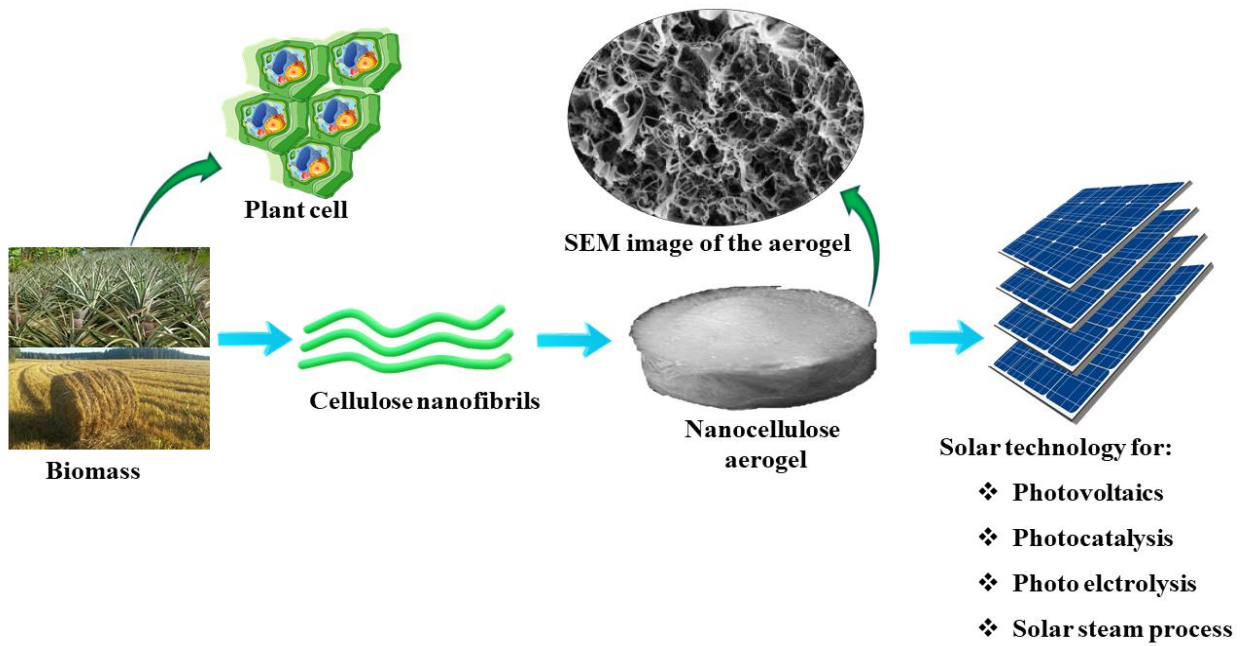


Fig. 5. The summary of the introduction section.

2. Solar thermal technology

Solar thermal technology works by absorbing solar radiation and turning it into heat energy, which is then transferred to a moving fluid below. It is different from solar photovoltaic which uses semiconducting materials to generate electricity. The efficiency of the solar thermal collection system could be improved by increasing solar thermal energy absorption and reducing the heat loss from solar energy receivers [19]. The primary solar collector (also known as the solar field), the solar receiver, and the power block make up a Concentrated Solar Power plant. Fig. 6. illustrates the schematic of a CSP Plant [20].

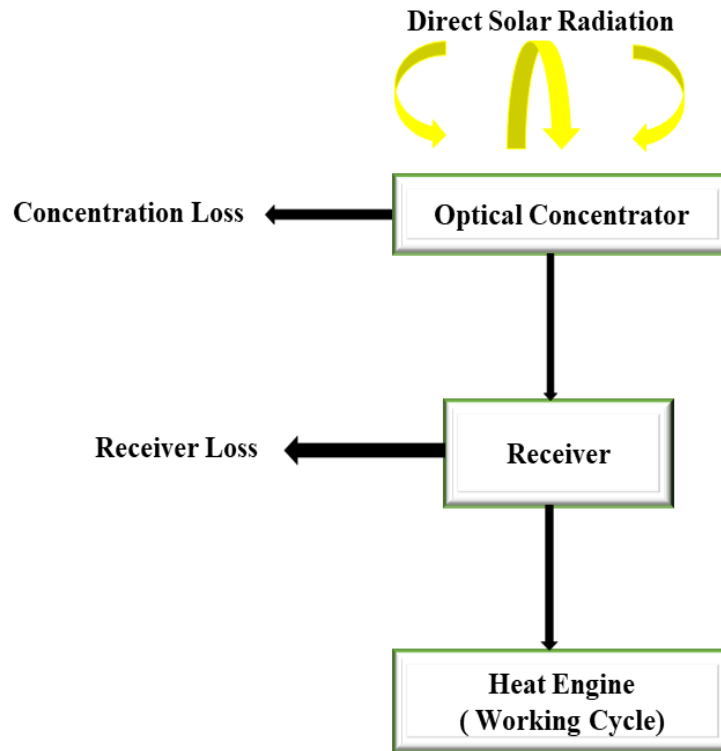


Fig. 6. Schematic flow diagram of a CSP Plant [20]. Modified with permission.

The receiver is the component that is placed at the collector's focus, which absorbs the solar radiation to heat the working fluid. The solar collector is the component that concentrates solar energy at the focus. The power block has heat engines that use the heated working fluid to turn the power cycle which leads to power generation [21]. The essential element that transforms and collects concentrated solar radiation that is incident from solar optical concentrating systems is a solar receiver. Solar receivers can be categorized using a variety of factors, including the receiver geometry, the heat transfer medium's phase (gas, liquid, or particle), whether the heat transfer medium comes into direct or indirect contact with solar radiation, and whether chemical reactions are included or not.

A receiver is designed to maximize the receiver absorption efficiency η_{rec} defined as the ratio of the absorbed radiative power Q_{net} in heat transfer media or chemical materials to the total radiative power Q_{in} reflected from solar concentrators [22]. The solar thermal receiver is frequently incorporated to receive the most out of concentrated solar thermal radiation. It acts as a thermal source for the working fluid. Commercial solar concentrating collectors are depicted in Fig. 7. A Parabolic Trough Receiver (PTR) has an absorber tube housed in an evacuated glass envelope. External tubular receivers mounted in CRS are made up of several panels of parallel absorber tubes. Linear Fresnel consists of an array of long parallel curved/flat mirrors/reflectors and a focal cavity receiver. The parabolic dish collectors focus the solar radiations on the receiver placed at the centre of the parabola curve [23]. One can increase receiver absorption efficiency by optimizing receiver geometries, increasing the concentration ratio provided by solar concentrators, decreasing the view factors from the inner surfaces of the receiver to the surroundings, and increasing the absorptivity of receiver surface materials.

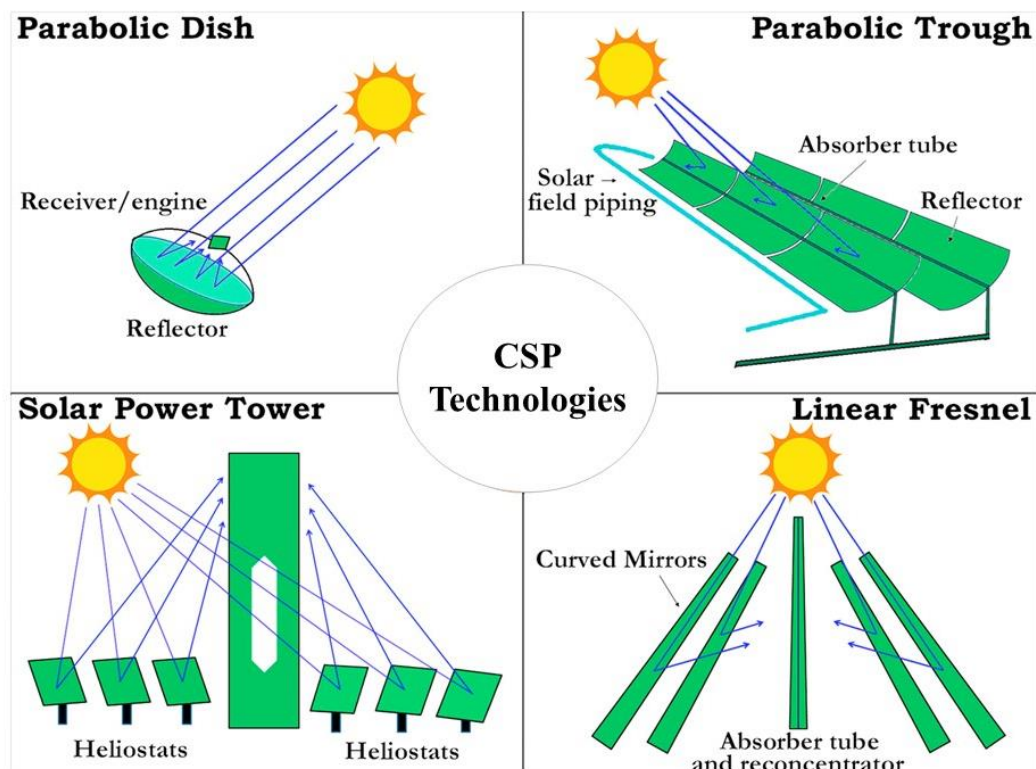


Fig. 7. Major CSP Technologies [24]

Two key parameters significantly affect absorber performance: material and geometrical properties. The efficiency and output temperature can be significantly influenced by the geometric properties of the absorber, porosity (the ratio of void volume to entire volume), and the number of pores per inch (PPI) of the porous absorber [25]. The major energy losses from solar thermal receivers are caused by convection, reflection, and radiative emission. Spillage and conduction through the supporting structure cause minor losses. The contributions of the various loss components to the total loss are affected by several factors, including receiver design, operating temperature, and atmospheric conditions. The limitations and trends of these combined influences are illustrated by considering: an ideal solar receiver (no convection/conduction heat losses and blackbody absorption).

The dependence of radiation losses on the fourth power of temperature also has important implications on the material and shape of the receiver. Radiation losses from a solar receiver can be managed by careful choice of surface material [7]. More research has been conducted to localize heat and use thermally insulated structures to reduce heat loss. These structures should share three key characteristics. The first efficiently absorbs the sunlight to produce heat. The second is a material with low thermal conductivity, which prevents heat from transporting away from the absorber surface. The third is a hydrophilic wicking surface to promote fluid flow to the surface. The efficiencies of solar thermal conversion are obtained from 57% to 85% by those structures in a certain intensity of solar irradiance [26]. Thermal radiation loss impedes high-efficiency solar receiver operation at high temperatures. The receiver geometries play an important role in optimizing all heat transfer modes (conductive, convective, and radiative). The position, geometry, and material of the absorber influence the performance of the solar collector used [27]. For any solar receiver, the receiver efficiency is defined as the where Q_{rec} is energy available at the receiver surface and Q_L is heat losses from the receiver.

$$\eta_{rec} = \frac{Q_{rec} - Q_L}{Q_{rec}}$$

High solar absorption, small thermal losses, and high optical concentration all contribute to a high receiver efficiency. Table 2 presents the various modelling strategies for evaluating the performance of solar receivers with governing equations used in each.

In general, the thermal efficiency of the solar thermal collector is given as:

$$\eta_{thermal} = \frac{m c_p (T_{out} - T_{in})}{GA} \quad [28].$$

where m is the mass flow rate, c_p is the specific heat of the heat transfer fluid, T_{out} is the fluid outlet temperature, T_{in} is the fluid inlet temperature, G is the solar irradiance and A the aperture area.

So, the major challenge is the heat loss, energy transfer, storage performance, and containment of materials of the receiver hindering efficiency improvement, cost-effectiveness & safe operation. Receiver and thermal storage devices designed through efficiency-improving approaches and fabricated with durable materials should be developed to keep up efficient and reliable operation [29]. An optimal receiver material exhibits high transmission in the solar spectrum ($\approx 95\%$, $\lambda < 2.7 \mu\text{m}$) and high absorption in the emitted IR spectrum ($\approx 100\%$, $\lambda > 2.7 \mu\text{m}$).

The key properties required for solar thermal technology application include high porosity, mechanical strength, optical properties, thermal stability, and thermal conductivity.

Model	Concept	Equation	Advantage	Disadvantage	Reference
Conceptual	Amount of radiation passed through the aerogel is an exponential function of thickness of the aerogel.	$k_g \frac{T_{g,i} - T_{g,o}}{L_g} = h(T_{g,o} - T_{amb}) + \sigma \varepsilon_g (T_{g,o}^4 - T_{amb}^4)$	<ul style="list-style-type: none"> • Ideal case • Less expensive 	<ul style="list-style-type: none"> • Not Realistic 	[127]
Detailed	Radiation intensity inside the aerogel is decreased due to absorption, out scattering and increased due to thermal expansion, in scattering.	$\cos \theta \frac{dI_{\Omega'}}{dz} = -(\kappa + S)I_{\Omega'} + KI_b + \frac{S}{4\pi} \int_{4\pi} \Phi_{\Omega \rightarrow \Omega'} I_{\Omega} d\Omega$	<ul style="list-style-type: none"> • Accurate Method • Acceptable availability of computing resources. 	<ul style="list-style-type: none"> • High computational cost. • Reconstruction of real geometry is complex. 	[42]
Rosseland Diffusion	Heat transfer inside the aerogel is considered to be one dimensional.	$\rho c \frac{\partial T}{\partial t} = \frac{\partial q_{cond}}{\partial z} + \frac{\partial q_{rad}}{\partial z}$	<ul style="list-style-type: none"> • Simple • Can be used for optically thick media. 	<ul style="list-style-type: none"> • Limited Accuracy 	[127]
Homogeneous Equivalent	It considers the volume of the absorber as a porous continuum.	$\frac{1}{\phi} \frac{\partial(\rho_f v_D)}{\partial t} + \frac{1}{\phi^2} \nabla(\rho_f v_D v_D) = -\nabla(P)_f + \frac{\mu_f}{\phi} \nabla^2 v_D - \left[\frac{\mu_f}{K_1} - \frac{\rho_f}{K_2} v_D \right] v_D$	<ul style="list-style-type: none"> • Less time consuming. 	<ul style="list-style-type: none"> • Limited Accuracy. • Selection of appropriate empirical terms is difficult. 	[128]

Table 2 Modelling strategies adopted for porous structures in solar thermal receiver.

3. Basic concept in a porous solar thermal receiver

Material	Pore size (μm)	Porosity (%)	Specific surface area (m^2/g)	Absorption (%)	Thermal Conductivity ($\text{W m}^{-1} \text{K}^{-1}$)	Reference
Fibre mesh			0.008	95.3	0.08	[30]
SiC catalyst	2000	--	0.001	96.0	--	[30]
Carbonized mushrooms	3.6	90	312.5	96	0.45	[31]
Plasmonic wood	5-50	--	--	99	0.45	[32]
Carbonized melamine foam	150	--	--	96.46	0.03	[33]
CNT-MoS ₂ film	0.02-0.2	--	--	95	0.06	[34]
Silica aerogels	0.02-0.1	85-99	600-1000	76-88	0.01-0.02	[35]
Carbon aerogels	0.002	98	300	96	--	[36]
Biomass aerogels	--	95	--	--	--	[37]
Cellulose aerogels	--	98	5.2-92.3	98	0.017-0.036	[38]

Table 3 Performance of different kinds of porous materials in solar thermal technology.

The hierarchical pore structure is one of the foremost significant aspects of high-performance energy storage. Pore size distribution is a very important criterion to characterize an aerogel. Porous materials provide a decent solution for improving the heat transfer characteristics in solar systems [39]. Table 3 summarizes the properties of the various investigated porous materials. In general, aerogels are solid lightweight materials with extremely low density

between 0.001 and 0.2 g/cm³, with over 90% porosity with the most prevalent pore diameter of 2–50 nm prepared by replacing the solvent of a gel with gas with very moderate shrinkage of gel solid network [40]. Aerogel refers particularly to the porous material with strict micropore sizes (pore diameters <2 nm.). These air-filled pores enhance the physicochemical properties and therefore the structural characteristics in the macro scale furthermore integrate typical characteristics of aerogels. The robust porous structures of the aerogel can ensure storage without subsequent leakage and may provide good thermal insulation for maintaining the temperature at the desired level [41]. Depending on the type/class of aerogel and fabrication method, the density of aerogels could range between 3 and 280 kg/m³ attributable to their high porosity in nature. McEnaney *et al.* [42] predicted to use of aerogel-based solar receivers which could reduce radiation losses and boost solar thermal conversion that spans a broad range of operating temperatures and optical concentrations, than vacuum-gap receivers. Aerogels enable a system to function at higher receiver efficiencies or to achieve the same receiver efficiencies at lower optical concentrations by minimizing heat losses while maintaining high solar transparency. Fig. 8. shown below is a schematic of an aerogel-based solar receiver. Strobach *et al.* [43] developed an optically transparent, thermally insulating monolithic silica aerogel, well-suited for solar thermal applications finding that receiver efficiency can be increased by 1%. He demonstrated that annealing duration affects the aerogels' solar transmittance and radiative characteristics, which can be leveraged to improve the aerogel's performance for CSP applications. Peng Mu *et al.* [44] synthesized conjugated microporous polymer (CMP) aerogel-based solar steam generators that show high porosity of greater than 94% mechanical properties with a compressive strength of up to 0.54 MPa under loading of 75% strain. The designable flexibility of CMPs creates a new opportunity for the rational design and construction of new CMP-based solar steam generators. This flexibility allows for the fine-tuning of the porosity

and chemical composition of the final CMP product using only a few changes to the CMP building blocks through a straightforward one-pot reaction.

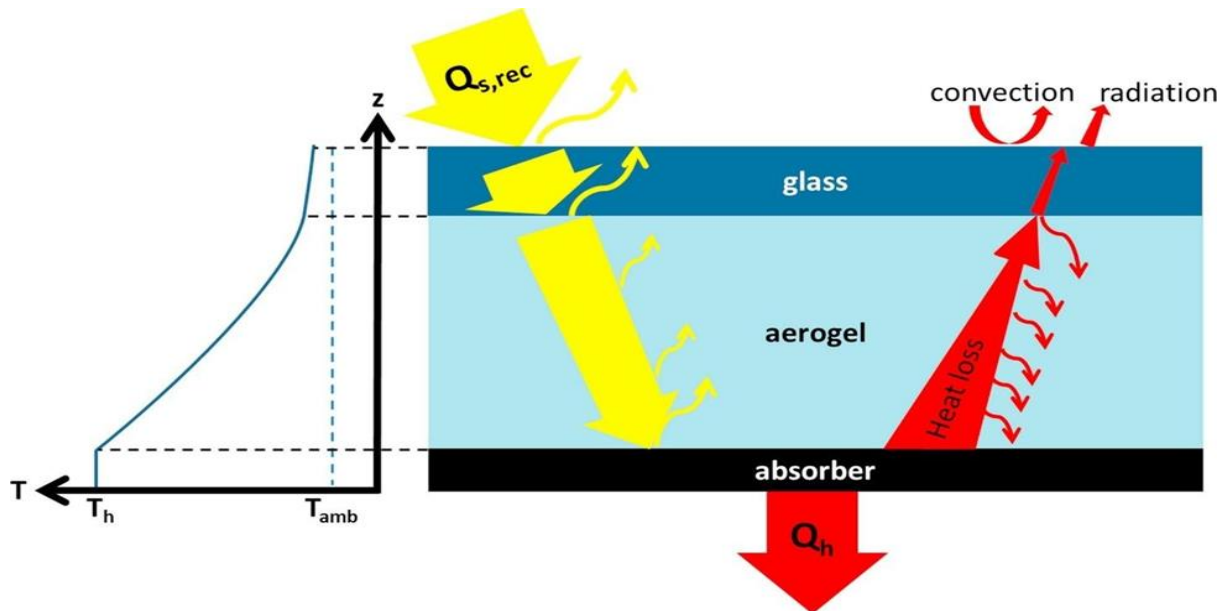


Fig. 8. Schematic of an aerogel-based receiver [45].

High mechanical strength often results from a high-density structure. The aerogels were reported to be physically robust and can support a static load of the maximum amount of 1 kg without any compression of the initial height [44]. Aerogel can maintain its elastic property even after ten compression cycles, which indicates high mechanical strength and good flexibility. The high operating temperature of the solar thermal application often requires the receiving materials to be thermally stable. Improving the performance of concentrated solar power (CSP) can be realized through the application of thermally stable aerogel as a solar thermal receiver with either minimal cost impact or design change.

The key parameter to differentiate the potential light-to-heat conversion performance of aerogel is its ability to capture an abundance of light while retaining the heat internally. A perfect absorber surface eliminates the transmittance and reflectance while exhibiting maximum absorption over a broad spectral range. The solar irradiation on the earth's surface is divided

into three parts as follows; 1) 5% for the ultraviolet region, which lies within 300 nm–400 nm, 2) 43% for the visible light region, which lies between 400 nm and 700 nm and 3) 52% for near-infrared (NIR) region lies within 700 nm–2500 nm wavelength span as shown in Fig. 9. The optical behaviour of aerogel focused on basic material properties, such as refraction index, transparency, and scattering. The latter is well present in aerogel; it was observed since the material's dis overly and in or porates a relevant impa t on radiation transfer. Aerogels have higher transmittances within the solar spectrum [46].

The photothermal materials must have a wide absorption capability covering the complete solar spectrum range (250–2500 nm).

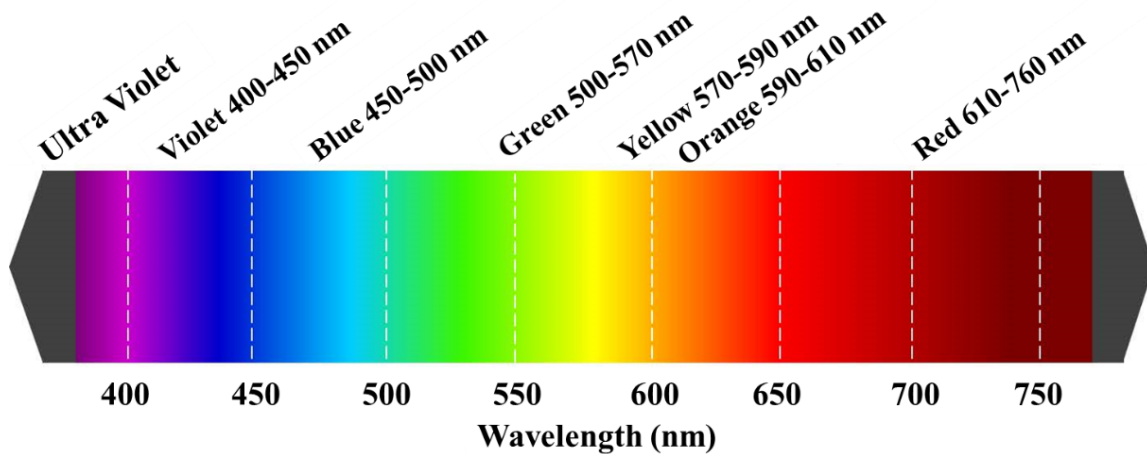


Fig. 9. Solar Irradiation Spectrum [19].

For aerogels, the absorption can be calculated by using the following equation

$$\alpha = -1 R T$$

Where α represents absorption, R is the reflection, and T is the transmission [47] For most of the dense solid materials, the refractive indexes are larger than 1.3. Aiming to reduce the

refractive index, porous solid material in which air replaces part of the solid is a good choice originating from the decreased electron density and permittivity [48]. Aerogel studies in the field started in the early 1990s, and aimed towards assessing relevant properties: transmittance, reflectance both spectrally and in the relevant bands of the solar spectrum, and the g-value (also named Solar Heat Gain Coefficient SHGC and Total Solar Energy Transmittance TSET). Except when noted, the optical properties refer to hemispherical values (which include the radiation transmitted/reflected in regular and scattering modes) [49]. Aerogel can naturally be opaque or transparent to solar radiation. It is transparent across the solar spectrum and opaque in the IR. Unique features in aerogel such as high porosity and low pore volume facilitate aerogels' potential in increasing the performance of solar thermal absorbers with minimal heat loss due to scattering. Scattering is resulting from the interaction between the incident light and the inhomogeneity of the receiver structure [50].

Thermal conductivity is a parameter used to predict insulator thermal performance. This parameter is achieved by a summary of three thermal conductivities: solid thermal conductivity (λ_s), gaseous thermal conductivity (λ_g), and radiation thermal conductivity (λ_r). The thermal conductivity of porous media depends on the random nature of the microstructure. The unique combination of the multiscale porous sheath and ultra-low density, aerogel collaboratively minimizes thermal conductivity by all these three mechanisms [51]. Aerogels have a gas phase that reduces the number of collisions between molecules, lowering thermal conductivity and limiting convective mass transfer. The thermal conductivity decreases with an increase in density and a decrease in porosity [49]. The aerogel's microscopically closed cellular structure prevents the gas currents that cause macroscopic convection, and the low density implies that there is very little material to conduct heat [52] for an aerogel as depicted in Fig.10. Aerogels are solid materials with 3D nanoporous structures. Therefore, the scattering of phonons by the solid-solid or solid-gas interfaces in an aerogel structure will reduce the contribution of λ_{sc} to

thermal conductivity. Due to a large number of multilevel solid–solid interfaces, aerogels always show strong phonon scattering characteristics, thereby leading to an occasional solid conductivity. As for thermal convection (λ_c), its contribution to the thermal conductivity of aerogel is sort of negligible. This is often because the pore size in aerogels is typically at the nanometer scale, therefore the heat transfer area of the surface is extremely small. The contribution of radiation (λ_r) to thermal conductivity for an aerogel under ambient temperature and pressure can almost be ignored. But under vacuum conditions, the contribution of radiation must be taken seriously. Under most atmospheric conditions, gas conduction (λ_{gc}) features a dominant contribution to the thermal conductivity of aerogel materials. The gas conduction is governed by the average pore size in aerogels and the mean free path of air molecules. For aerogels, the mesoporous (2–50 nm) pore favours the Knudsen effect, which means the circulation of air molecules is confined inside pores (i.e., pore size smaller than the mean free path of air molecules), thus leading to low gas conduction [53]. These properties make aerogels excellent insulators, although at higher temperatures radiation within the aerogel can have a major impact on the effective thermal conductivity.

Recently, there have been innovative approaches that are widely being employed beyond conventional freeze drying and CO₂ drying for developing solar thermal receivers. Li *et al.* [54] have developed a dynamic photothermal coating for steam generation devices that demonstrates flexible switching between different installations with stable photothermal conversion ability using gallic acid (GA), Fe(III) and hydrophilic poly(vinylidene fluoride) (PVDF) via simple deposition of gallic acid (GA) and Fe(III) on the surface of the PVDF membrane. The resulting coating has achieved an excellent evaporation rate of 1.539 kg m⁻² h⁻¹ and with a steam generation efficiency of 90.2% under 1 sun illumination. Moreover, it can be recovered in acid washing and is reusable for up to 150 cycles. This demonstrates a new direction for new nanocomposite for solar applications. Zhange *et al.* [55] have adopted another

approach of using sustainable and relatively inexpensive materials for the development of solar evaporators. They used tannic acid and iron (III) and fabricated the solar evaporator via three-dimensional (3D) printing. Owing to the better control of the technique, they have used a conical array surface structure to promote the light-harvesting capacity. By optimizing the height of the conical arrays and other parameters, they have managed to obtain an outstanding high evaporation rate of $1.96 \text{ kg m}^{-2} \text{ h}^{-1}$ under one sun illumination, with a photothermal conversion efficiency of 94.4%. This work demonstrates the importance of pore characteristics and optimization, also the competency of natural materials for solar application where most of the studies revolve around expensive materials.

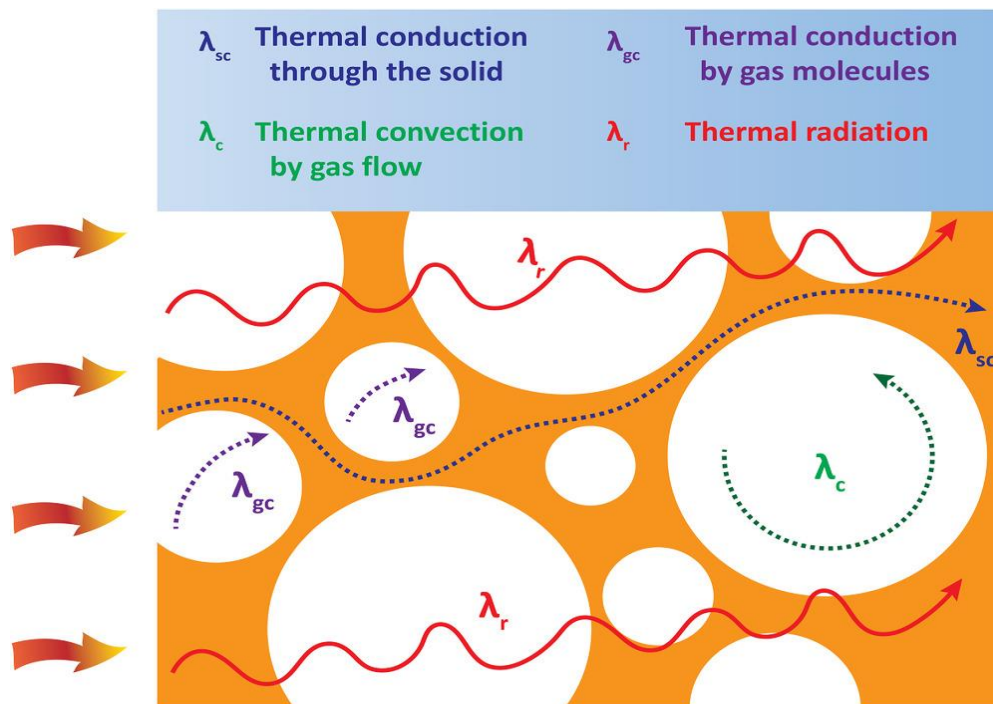


Fig. 10. The schematic diagram of the thermal conduction mechanism of an aerogel [53].

Higher absorption and optimum light scattering within the solar material are important characteristics necessary for an aerogel for solar applications. Hence, materials with high transparency and optical haze values are normally preferred. Silica aerogels which currently dominate the solar application typically scatter electromagnetic radiation in the ultraviolet wavelengths severely, causing high optical loss, which eventually offsets their performance as receiver applications. Whereas, the nanocellulose aerogels have highly reactive OH groups that allow facile surface modification and high-performance bonding with conductive fillers via covalent or hydrogen bonds. Owing to these reactive surface groups, chemical modification and higher stability of nano cellulose can be achieved [56]. For the further advancement of versatile energy storage systems to develop solid film/aerogel substrates, nanocellulose fibres with a high aspect ratio, such as those extracted from higher plants or that build entangled web-like structures, can be used. The ability of cellulose nanofiber aerogels to exhibit well-defined pore morphologies and selective sorption properties has drawn significant interest for extremely high specific surface areas due to their anisotropic structure which is necessary for energy storage application [57].

4. Significance of nanocellulose and cellulose aerogels

The study of green and biodegradable aerogel has piqued the interest of researchers, who are increasingly concerned about the sustainability of technologies. Nanocellulose aerogels demonstrate extraordinary mechanical properties as a function of density. CNF is easily assemblable into a 3D porous aerogel structure with high structural integrity and resilience. Traditional aerogel materials such as silica (SiO_2), carbon, and tin dioxide, which have been favoured by several researchers as inexpensive and environmentally friendly alternative materials for aerogel synthesis, can also be compensated for by nanocellulose-based aerogels due to their brittleness, complex equipment and renewable[58]Fig. 13. presents the synthesis route of porous cellulose nanofiber aerogel.

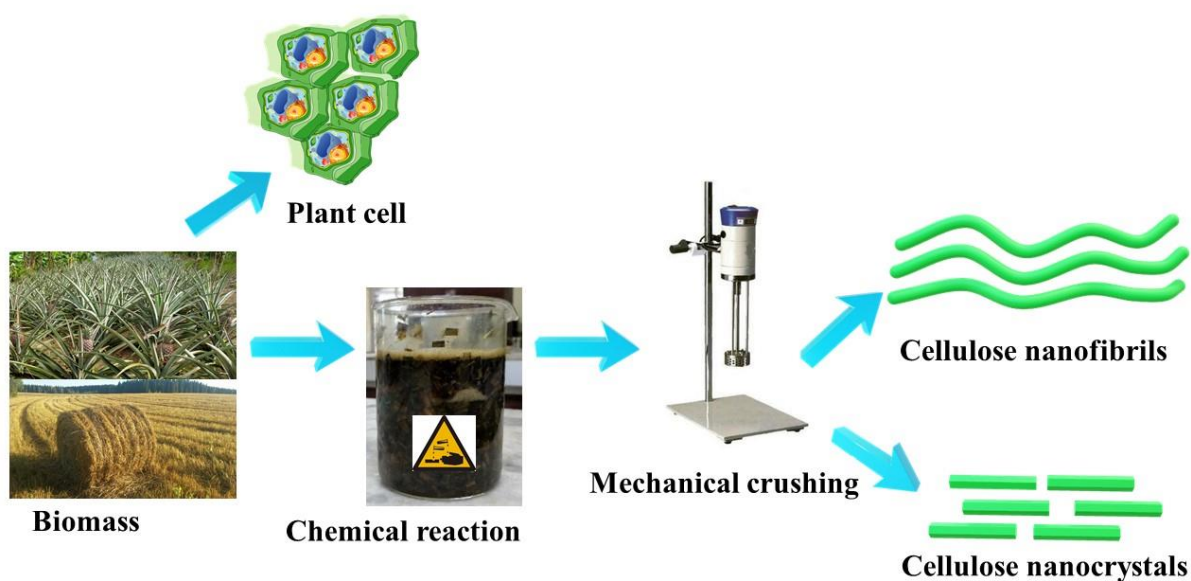


Fig. 11. Schematic illustration of extraction of nanocellulose from biomass.

From a strict chemistry point of view, nanocellulose is a syndiotactic homopolymer polysaccharide that has β -1,4-anhydroglucopyranose as the repeating unit. In general, different biomasses are the main resource for nanocellulose. However marine animals such as urochordates and microorganisms like bacteria are also sources of nanocellulose [59,60]. Interestingly, bacteria-based nanocellulose is among the purest form of nanocellulose and is extensively used in biomedical applications. Regardless owing to the abundance of biomass, cellulose is known to be the most abundant natural polysaccharide followed by chitin which is extracted mostly from marine living organisms [61]. Nanocellulose can be classified into mainly three classes and they are cellulose nanocrystals (CNC), cellulose nanofibers (CNF), and bacterial cellulose (BC). Fig. 11. Demonstrates the extraction of nanocellulose from biomass. However, bacterial cellulose is nanocellulose extracted from bacteria that have fibrillar and crystal structures similar to CNFs and CNCs extracted from biomass respectively. Thus from the overall characteristics, cellulose can be referred to as cellulose nanofibers and cellulose nanocrystals. However, from a solar application perspective, the nanocellulose employed is

mostly biomass-derived nanocellulose owing to its relative economical appeal [62,63]. In terms of both length and diameter, CNCs have dimensions in the nano range, whereas CNFs have a length in the micrometre and a diameter in the nanometer. With the development of nanotechnology, the selection of more specific nanomaterial suited for the application has greater importance that has developed in identifying a new type of nanocellulose such as cellulose hollow fibres [64,65]. Hence differentiating cellulose types are important for the selection of suitable nanocellulose uniquely for solar application. While different types of cellulose nanofibers are available in the domain, the cellulose nanofibers derived from biomass have been dominating the solar application.

Cellulose nanofibers (CNF) are natural nanoscale fibres, consisting of purely cellulose molecules. Regardless of the origin, biomass-derived cellulose is fibrous, strong, and linear that has features attributing to the resultant fibres with varying characteristics. Moreover, depending on the source and the chemical processing, parameters including shape, aspect ratio, surface chemistry, crystal structure, and degree of crystallinity can be controlled. These fibres have shown remarkable mechanical properties compared with other natural fibres as well as glass and carbon fibres [66]. In the microstructure, the cellulose materials have the propensity to self-associate and form an extensive network consisting of both intramolecular and intermolecular hydrogen bonding derived from the surface hydroxyl groups as seen in Fig. 12 [67,68]. These hydroxyl groups enable modifications that further diversify the application potential of cellulose nanofiber that has previously been thoroughly explored [69]. Among the inherent characteristics, the mechanical property, film-forming capacities, transparency, and low thermal conductivity are the main properties that have been mostly explored.

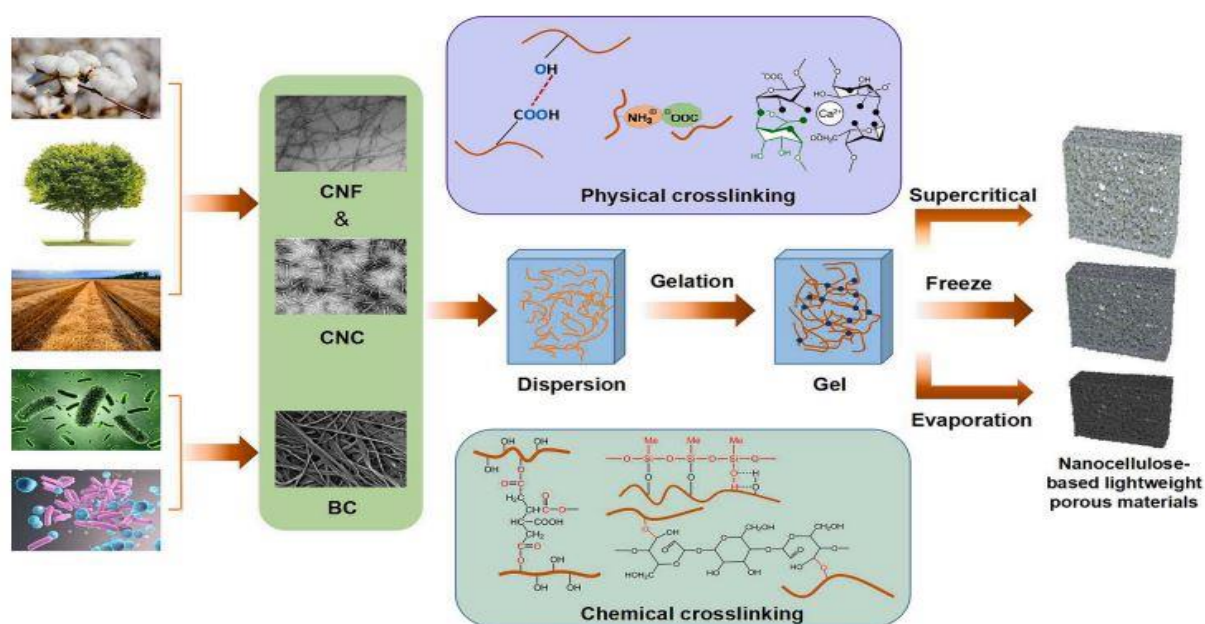


Fig. 12. Synthesis of nanocellulose-based aerogel [70].

NFCs typically range in length from 5 to 100 nm and in diameter from hundreds of nanometers to a few micrometres. The bulk density (ρ), measured by dividing the weight (m , mg) by the volume (v , cm^3), of lightweight and porous nanocellulose aerogels, usually fluctuates between 1 and 100 mg cm^{-3} [58]. The CNF aerogel derived from rice-straw cellulose exhibits high porosity, measuring up to $41.8 \mu\text{m}$ average pores size[71].

Owing to the excellent mechanical characteristics and film-forming capacity, a robust, stable, porous, flexible, and insulating material can be fabricated with cellulose nanofibers. This is evident in numerous articles that have been published with neat nanocellulose as the reference material [72,73]. This was enabled by extensive studies that were carried out on cellulose nanofiber leading to the extraction of cellulose fibre with excellent mechanical characteristics. For instance, the cellulose nanofibrils extracted from the flax exhibit mechanical strength as high as 1830 MPa. This when compared with synthetic fibre like E-glass which has a mechanical strength of 2000 MPa, demonstrates the huge application potential of the cellulose

nanofiber. Moreover, cellulose nanofiber exhibited a lower density of 1.5 g/cm^3 compared to the 2.5 g/cm^3 of the E-glass [74]. In terms of film-forming capacity, the characteristics are mostly derived from the fibular structure in combination with reactive hydroxyl groups that participates in intermolecular interactions. The strong physical interaction, as well as fibrillar entanglement, helps nanocellulose to form composites [75]. Thermal conductivity and thermal insulation characteristics of cellulose fibres are derivatives of four parameters such as crystallite thickness, fibre orientation, and interfacial thermal resistance between fibres and small pores. Uetani *et al.* [76] have studied in depth and summarized these aspects specifically for cellulose nanofibers. Finally, the transparency of nanocellulose fibres is ambiguous as nanocellulose fibre is referred to as both opaque and transparent. Several articles have been published on nanocellulose fibre modification that leads to enhanced transparency has also been published [77,78]. However, the unmodified nanocellulose fibre films that demonstrated transparency have undergone strong mechanical treatment that has resulted in reduced mechanical strength. In comparison, the unmodified cellulose films have higher haze values [79,80]. Hence, higher transparency is generally achieved with chemical modifications.

Because of the high strength of nanocellulose and the stable porous structure of the formed aerogel, nanocellulose aerogels frequently exhibit good mechanical performances under an external force, including compressive strength, Young's modulus, and flexibility, outperforming traditional brittle SiO_2 aerogels, which are typically broken easily under pressure [81]. The CNF comprises parts of the crystal structure that are crystalline and amorphous. Young's modulus of the CNF aerogel is generally superior. Nanofibrils have a much smaller lateral dimension and a higher aspect ratio, which can aid in the formation of a strong entangled network. In the axial direction, Young's single-crystal cellulose I module achieves up to 134 GPa [82]. Young's single C F wood modulus and tensile strength are 30–40 and 2–3 GPa, respectively [83]. CNF is widely used as a building block for the development of robust aerogels

due to its high modulus and strength. Despite being free of cross-linkers, the CNF aerogels exhibit a high compressive strain of around 70%. Physical entanglement and retained chemical intramolecular hydrogen bonding provide high mechanical efficiency. Numerous attempts have been made to enhance the performance and improve the mechanical strength of cellulose aerogels by adding inorganic fillers such as TiO₂[84], nano-silica[85], hydroxyapatite [86], and graphene [87]. Pragma *et al.* prepared nano-fibrillated cellulose aerogel from pinewood which displayed cyclic compression of 70% at 25% strain. This is mainly due to the densification of aerogel at a higher strain rate and the dense assembled structure of the aerogel [88]. Ya Liu *et al.* prepared CNF aerogel with excellent mechanical properties which displayed 0.25 MPa compressive strength. The high compressive strength was due to the hydrogen bonding interactions between CNF and BNNs [89]. Zhu Wu *et al.* [90] prepared covalently cross-linked CNF aerogels through silane condensation and freeze-drying. It showed outstanding underwater mechanical toughness due to the anisotropic lamellar structure which exhibited random porous structures in both axial and radial directions. Fig. 13 (a) – (i) illustrates the mechanical properties such as density, lightweight, and flexibility of the CNF aerogel.

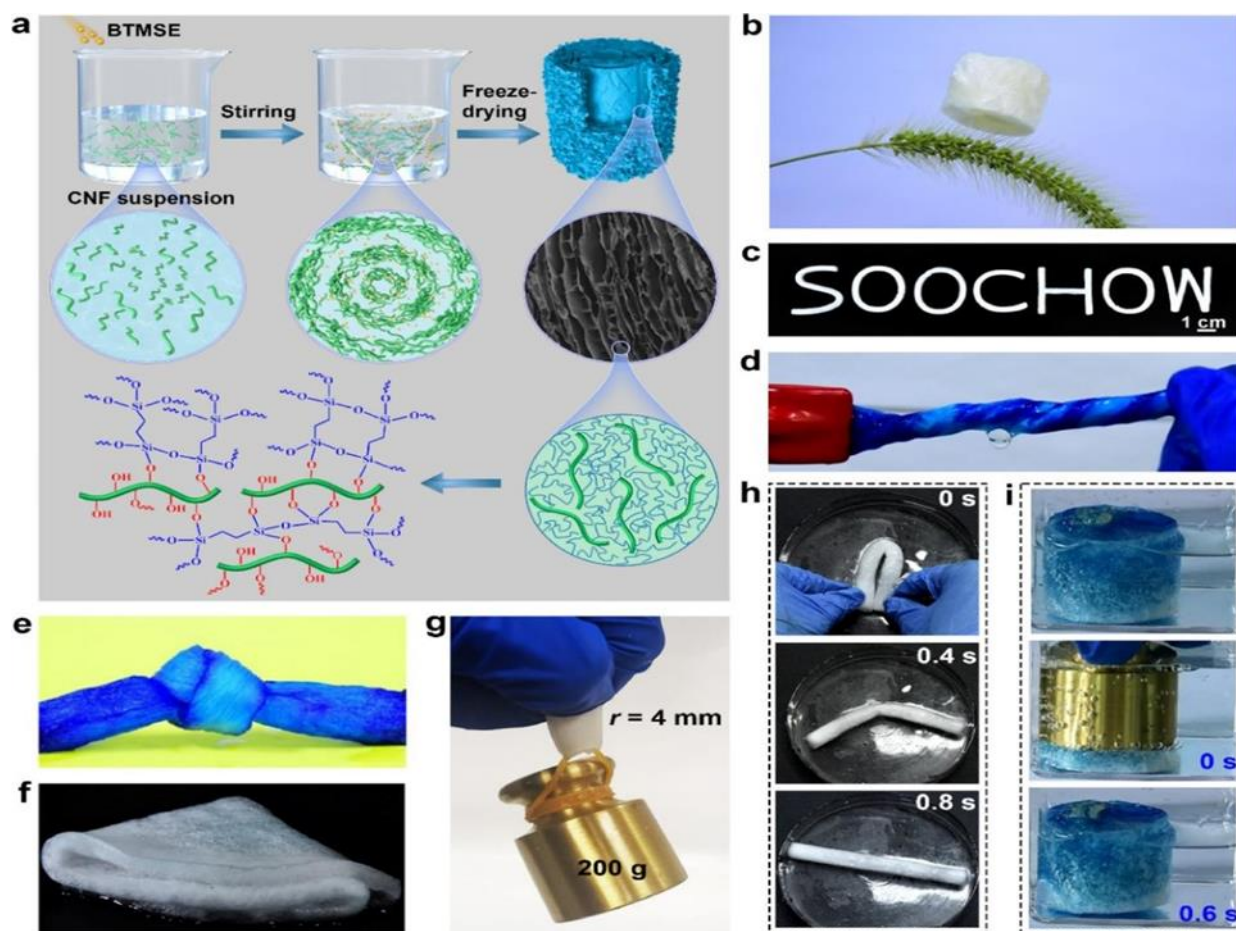


Fig. 13 (a) Scheme illustrating the fabrication of covalent-cross-linked CNF-based aerogels through condensation between CNF and BTMSE and subsequent freeze-drying. (b) Dry Si-CNF aerogel standing on top of a dog tail grass. (c) Si-CNF aerogels with diverse shapes. Photos showing water-swollen Si-CNF aerogel: (d) twisted along the axial direction, (e) knotted, (f) folded, and (g) with a tensile load of 200 g. Photos showing shape recovery of Si-CNF aerogel in water: (h) folded and (i) compressed to 20% of the original height along the axial direction [90].

Owing to the superior optical characteristics of nanocellulose in comparison to the inorganic counterparts, nanocellulose-based aerogels are considered to be an appropriate alternative to inorganic polymer-based aerogels. Nanocellulose aerogels have been examined for the production of transparent solar receivers. A higher level of transparency can be achieved by pre-treatments such as TEMPO oxidation, carboxylation, etc. CNF has a very smooth surface morphology, hence no polishing or surface planarization is required for solar cell production. Nanocellulose aerogels with a unique 3D-ordered liquid crystalline structure were recently

reported to combine toughness and transparency [91]. The unique properties of nanocellulose, including its high aspect ratio, abundant hydroxyl groups, and tunability, make it well-suited for creating lightweight, durable, and flexible aerogels. By incorporating crosslinkers or introducing compatible materials, the strength of the NC aerogel can be enhanced, while additional functional groups can be introduced to further expand its range of applications. The nanocellulose aerogel has been evolving owing to the generation of new groups or components generated in the aerogel system. This can be summarized into 3 basic groups: 1. Direct addition, 2. Coprecipitation and 3. Coating. This has helped to impact various new characteristics of the nanocellulose aerogels such as electricity, thermal performance, hydrophobicity, magnetism etc [92]. This makes the nanocellulose aerogels suitable as a versatile material that can be used for many applications including flexible sensors for monitoring the daily behaviours of the human body, biomaterials for wound dressing, scaffolds for tissue culture, and drug delivery systems, EMI shielding, Thermal and electrical insulation, sensors, batteries and super capacitors etc. Among them, nanocellulose-based aerogels with or without modifications for solar applications also gained significant attention in recent times [93].

5. Cellulose Nanofiber aerogel for solar application

Cellulose has low solid thermal conductivity, which makes nanocellulose-based lightweight porous materials have broad application prospects in thermal insulation. High-performance aerogel fibres for low thermal conductivity are only explored to a very limited extent. However, these limitations have been addressed in different research works where nanocellulose aerogels have been synthesised along with a suitable material. Bai et al. [94] have developed nano cellulose and lignin-based aerogel for steam production and electricity generation. The authors have claimed to achieve a high evaporation rate was achieved up to $3.93 \text{ kg m}^{-2}\text{h}^{-1}$ under one sun irradiation and continuously generate electricity with an output voltage of 77 mV. The

reported work has employed carbonizing (modification) of lignin to improve solar adsorption and combined it with a nanocellulose aerogel. This type of approach can be complex and require higher operation costs. However, the other main approach includes the preparation of a composite with the material having suitable properties. Zou et al. [95] have developed a mussel-inspired, low-cost, polydopamine-filled cellulose aerogel that is employed for solar-driven water remediation. In this work, by effectively utilizing the numerous functional groups present in the polydopamine surface that includes catechols, amines, and imines to enable the interaction with nanocellulose. Moreover, the PDA has shown strong light-harvesting capabilities and photothermal conversion performance, making the nanocomposite aerogel useful for solar-powered water desalination and overcoming the limitation of the nanocellulose. Ding et al. [96] have developed nanocellulose-based aerogel for solar-thermal desalination and humidity sensing applications. Here in this work, the authors have used exfoliated $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheets and polyvinyl alcohol (PVA) to enhance the properties of the aerogel. Normally the aerogel with an oriented porous structure usually exhibits relatively high thermal conductivity (over $300 \text{ mWm}^{-1}\text{K}^{-1}$) in the evaporation direction. This was further enhanced by the use of $\text{Ti}_3\text{C}_2\text{T}_x$ nanosheets, which possessed stronger solar absorption and polyvinyl alcohol. The use of PVA here in this work is mostly aimed at cross-linking applications. The improved structural stability can provide a synergetic effect for the nanocomposite aerogel.

By regenerating in a high-concentration aqueous solution of AMIMCl (1-allyl-3-methylimidazolium chloride) and then drying with supercritical CO_2 . Mi, *et al.* [97] hence created flexible and transparent nanocellulose aerogels from an AMIMCl solution of cellulose. Because the presence of AMIMCl modifies the gelation process of nanocellulose resulting in a uniform nanoporous structure. By changing the regeneration bath from water to AMIMCl the transparency increased. Hence the porous network structure of cellulose aerogel contributes to the high absorbance of solar radiation by effectively blocking reflectance. Fibre-based hybrid

aerogels exhibit more than 97% light absorption from the ultraviolet region to the infrared region [98]. Nanocellulose aerogels have been reported to present a thermal conductivity below $25 \text{ mW m}^{-1} \text{ K}^{-1}$, close to air thermal conductivity [70]. Since the "mean free path" of air (between 60 and 100 nm) is much bigger than the pores of cellulose-based aerogels, there is no convection and very little gas conduction via the air molecules. Since the contribution of the solid network to thermal conductivity decreases with increasing porosity whereas due to air in pores increases, aerogels tend to have a minimum in the thermal conductivity versus porosity dependence. The CNF aerogel's cellular structure restricts airflow, making it an effective convective inhibitor, while its low transparency to infrared light prevents radiative transmission. For cellulose and cellulose-based hybrid aerogels, this is within 87–96%, depending on composition, where thermal conductivities \approx of $40\text{--}50 \text{ mW K}^{-1} \text{ m}^{-1}$ can be achieved [99] as shown in Fig. 14. In another study, Li *et al.* [100] have developed highly ordered and anisotropic hybrid materials by freeze-drying cellulose nanofibrils and silver nanowires. The resulting composite phase change materials (PCMs) exhibited a 72.7% increase in thermal conductivity which claimed to be near-theoretical thermal enthalpy. The approach can develop thermally stable composites that offer insights into the anisotropic thermal transmission and are potential candidates for renewable thermal energy storage. These studies demonstrate the influences of both the mean free path and the material selected for the nanocomposite preparation.

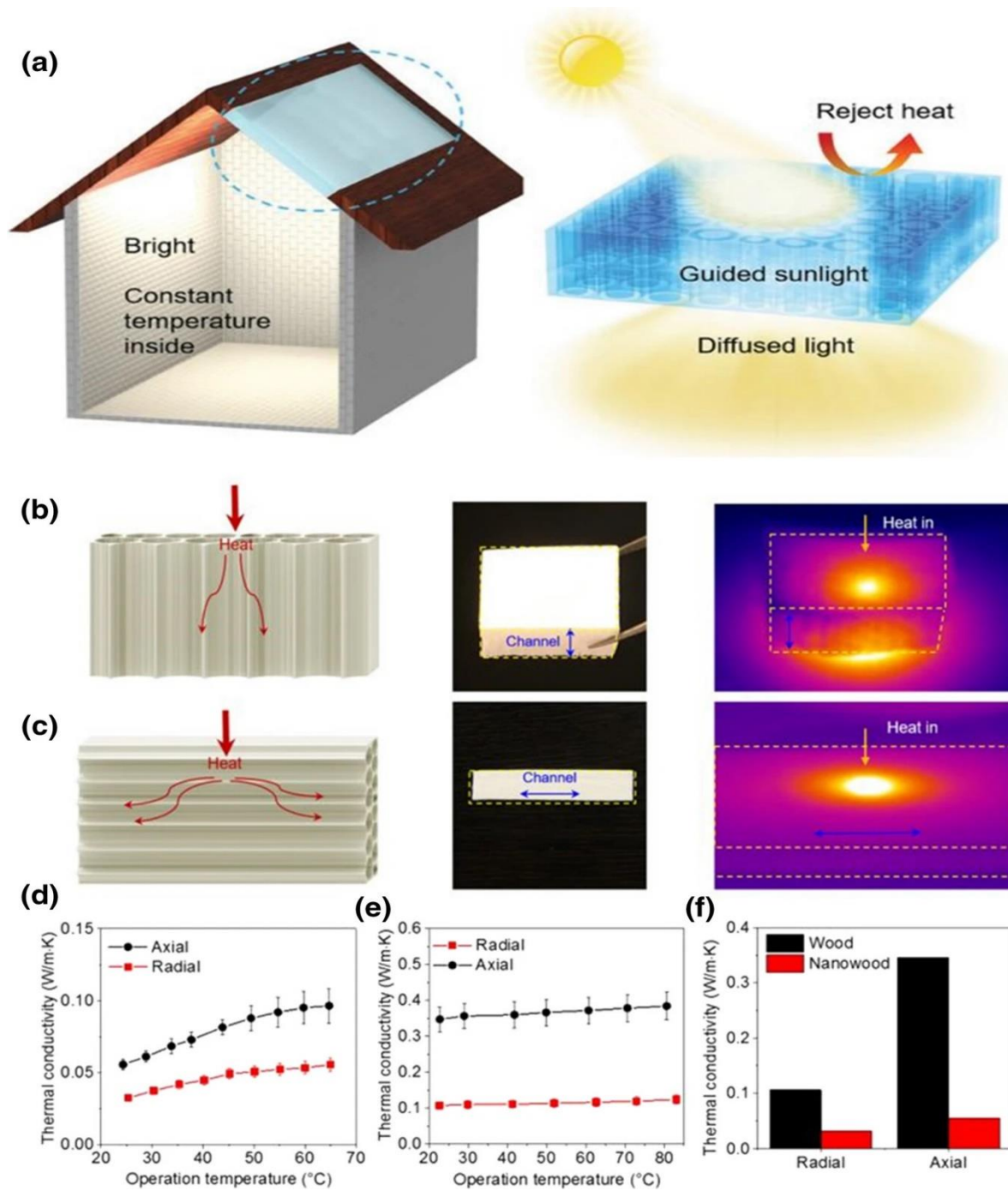


Fig. 14. (a) The application of transparent wood as the light-harvesting building material (b) Schematic representation of heat conduction along the wood cell walls as axial heat transfer, (c) heat conduction across the cell walls and hollow channels (d) Measured thermal conductivity of the nanowood from room temperature to 65 °C. (e) Measured thermal conductivity of the original wood from room temperature to 80 °C (f) Comparison of the thermal conductivity of the natural wood and nano wood at room temperature [101].

Thermal conductivity, in particular, is impacted by the various pore arrangements in cellulose aerogels.; Aerogels with no pore alignment had lower thermal conductivity than aerogels prepared with oriented pore distribution at about 0.024 W/m K [102]. Jian Zhou *et al.* [103] have successfully engineered highly porous and strong coaxial cellulose-rich fibres consisting of multiscale porous CA/PAA sheath and CNF aerogel core as novel thermal insulation materials. The better insulation performance obtained can be attributed to the introduction of aerogel in the core thereby restraining the air circulation to limit convective heat transfer. Jiménez-Saelices *et al.* [104] also evaluated the thermal properties of cellulose aerogels as a function of different pore organizations. The aerogels were formed from cellulose nanofibril suspensions by freeze-drying, using two different moulds subjected to different temperature gradients. Two instances were examined: an aerogel with oriented pore channels and an aerogel without pore alignment. Aerogels manufactured without pore alignment had more effective thermal insulating capabilities than aerogels with oriented pore distribution, and they obtained the lowest thermal conductivity at a fixed density of $0.024 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ as they have a cellular structure [105].

Another main area of cellulose nanofiber aerogel for solar application is solar evaporators. Even though carbon materials are recommended in this domain owing to their low cost and stability, cellulose-based hydrogel/aerogel and wood are also gaining attraction. The advantage of nano cellulose is that its assembled substrates offer easier structure regulation. The evaporation speed must be improved by reducing the evaporation enthalpy for the nanocellulose-based aerogel to be more efficient [106]. Wei *et al.* [107] developed a two-dimensional (2D) evaporator using layer-by-layer self-assembly and freeze-drying techniques. The evaporator consisted of cellulose nanofibers (CNF), $\text{Ti}_3\text{C}_2\text{Tx}$ (MXene), lignin (PL) and polydopamine-modified lignin (PL) materials. The introduction of lignin improved the light absorption and photothermal conversion performance of the evaporator owing to the strong

onjugation and π - π molecular interactions. This contributed to the C F/MXene/PL aerogel having enhanced light absorption performance (surface temperature could be reached to 39 °C under 1 sun irradiation) and higher evaporation rate (1.60 kg m⁻² h⁻¹). Li *et al.* [108] have developed a cellulose aerogel-based composite for efficient solar evaporation. In the work, they controlled the pore size of the aerogel was adjusted by controlling its carboxymethyl nanocellulose content. They have observed a direct correlation between the channel diameter of the aerogel-based evaporator and the water transport rate when the channel diameter of the aerogel increased from 21.6 to 91.9 μ m, the water transport rate increased from 31.94 to 75.84 g min⁻¹. This key information could pave the way for future studies however it's important to note the use of expensive materials like Mxene, Graphene derivatives in these approaches.

As studies with nanocellulose have increased exponentially, numerous research works on this particular area have been published. The below-mentioned table 4 summarises recent works published on nanocellulose-based aerogel for solar applications.

Composition	Drying method	Structural characteristics Porosity (%) Surface area(m ² /g)	Solar efficiency (%)	Application	Reference
CNF + CNT	Freeze drying	Porosity: 99.4-99.5	97.5	Solar steam generation	[109]
CNF	Freeze drying	Porosity: 99.4-98.6 Surface area: 15.2-92.3	--	Thermal insulation	[88]
CNF+ PEDOT: PS	Freeze drying	Porosity: 99.4 Surface area: 5.2-92.3	98	Solar steam generation	[110]

CNF+RGO+S A	Freeze drying	Porosity: 48.9- 65.9	91.5-93	Solar evaporation	[111]
CNF	Freeze drying		95.9	Solar steam generation	[112]
CNF+CNT	Freeze drying		96	Solar steam generation	[113]
CNF+BNNS	Freeze drying	Surface area: 99.49	--	Thermal insulation	[89]
CNF+PLA+P DAN	Freeze drying	Porosity: 98	90	Solar evaporation	[114]
CNF+CS	Freeze drying	Porosity:90 .16	94.3	Solar evaporation	[115]
CNF	Freeze drying		90.09	Solar desalination	[116]
CNF+PLA+P ANI	Freeze drying	Porosity:98	94.6	Solar evaporation	[117]
CNF+BP	Freeze drying		87.6	Solar thermal conversion	[118]
CNF	Freeze drying	Porosity: 97.8	--	Thermal insulation	[119]
CNF	Spray freeze drying	Porosity: 99 Surface area:80-100	--	Thermal insulation	[120]
CNF+PI+PR		Porosity: 92.28 Surface area: 86.23	82.5	Solar thermal conversion	[121]

Table 4 Properties of interest of cellulose nanofiber aerogel in solar thermal application

6. Conclusions and future outlook

Nanocellulose has the potential to address the global energy crisis and environmental deterioration caused by our reliance on fossil fuels. The ease of availability along with striking features including biodegradability, sustainability, low toxicity, high mechanical strength and flexibility are important characteristics that are necessary for a futuristic material. This review reports the advancements in the employment of CNF-based aerogels for solar energy-based applications. CNF-based aerogel has the potential in replacing current materials owing to its thermal insulation characteristics, film-forming capacity, and outstanding mechanical strength. It is also important to know that nanocellulose is among the most explored materials in terms of extraction and modification. Nanocellulose has revolutionized many industries such as biomedical applications, water purification, thermal and electrical insulation, EMI shielding, etc. The ever-expanding nature along with global green movements could further accelerate the potential development of nanocellulose in many more areas such as solar energy applications. As countries are looking for fossil fuels due to any reason including geopolitics, accessible green energy resources like nanocellulose could be at the forefront.

Market research and exploding scientific studies are pointing towards a further increase in nanocellulose production and development that could result in nano cellulose being less expensive, addressing the major drawback. Some of the major drawbacks that persist include non-transparency, low thermal stability, the requirement for modification, non-ecofriendliness of the current extraction technique, etc. Several approaches have been employed to address the drawbacks. For instance, the non-transparency or low transparency has been addressed by modifications such as acetylation, TEMPO modification, Copolymerization with suitable materials like PMMA, and solution casting or regeneration of cellulose [122,123]. The low thermal stability of the nanocellulose has also been addressed with modifications such as phosphorylation, chlorination or the addition of thermally stable materials like phosphates,

carbon derivatives, and inorganic additives, etc [124–126]. In general, the chemical modification of the nano-cellulosic material as well as the use of appropriative additives could address many of the current drawbacks associated with certain characteristics of nanocellulose in the solar application. However, these requirements for a chemical modification itself often create certain problems. The modification demands the use of harsh acidic chemicals or toxic materials which are needed to be disposed of with great caution and often compromise the greener approach itself. The incorporation of suitable additive materials into the composite instead of complex modification could be an approach. Another method is the emerging scientific interest in the development of a greener method itself using sustainable resources. The solar thermal systems must work in all weather. At present, almost all efforts are concentrated on the generation of steam during the daytime. Natural solar radiation can be reduced in strength due to many factors, including weather, climate, and geographical circumstances. The development of a system that can produce steam at all times of day must be considered to take solar thermal technology to a broader aspect and future. The summary of the current situation and the future perspectives of nanocellulose aerogel for solar application is schematically represented in Fig.15.

The prevalent employment of such a biodegradable and sustainable aerogel derived from nano cellulosic materials is the future. However, certain areas need to improve to enable applications in wider areas. Furthermore, the investigation and exploration of the development of different types of nanocellulose, the scale of nanocellulose production, and methods of production are pointing toward nanocellulose being the futuristic material of choice. Moreover, the ever-growing need for energy demand in connection with climate change, geopolitics, greener movements, and policies directs sustainable energy sources like solar energy generation as the upcoming breakthrough technology. Hence the combination of nanocellulose in various areas of solar-based energy applications needs to be studied.

Despite several major advantages, CNF aerogel-based solar thermal technology is faced with important challenges. There is a mismatch between current state-of-the-art and practical applications. To gain acceptance from potential customers, low-cost and large-scale manufacturing must be developed. There is currently no report on the estimation of manufacturing scalability and cost of materials, structure, and system, which creates a barrier to practical applications. Cost estimation and sizable scalability become a new potential method for presenting novel research conclusions. The stability of the system is still a challenge for the development of real devices. The long-term stability of solar-absorber materials has received little consideration. It is of great interest because it is working against high-temperature sources of heat and weather. Fabrication of large systems with stable performance for a long period should be paid attention to. The ability to design new materials and structures is still limited by a better understanding of the dynamic kinetics of these processes and the associated structure-property relationships. Fully understanding light transfer, thermal diffusion behaviours, and kinetics are crucial for optimizing materials, and structural designs. The light transfer is highly related to pore structure and surface properties while the thermal diffusion behaviours consist of conduction, radiation, and convection which focuses on minimizing heat loss.

This review article offers a thorough overview of the various aerogels that can be used in solar thermal technology as porous receiver layers. It covers the techniques of drying and precursor materials used in their synthesis. These aerogels' distinctive qualities, namely their transparency and hydrophilicity, are emphasized as important aspects that improve their appropriateness for incorporation into solar thermal collection systems. The transparency and hydrophilicity of these highlighted aerogels need to be improved further to ensure the practicality of solar thermal systems. Additionally, it is recommended to conduct additional studies to assess the technical and economic feasibility of incorporating aerogels into hybrid

systems.

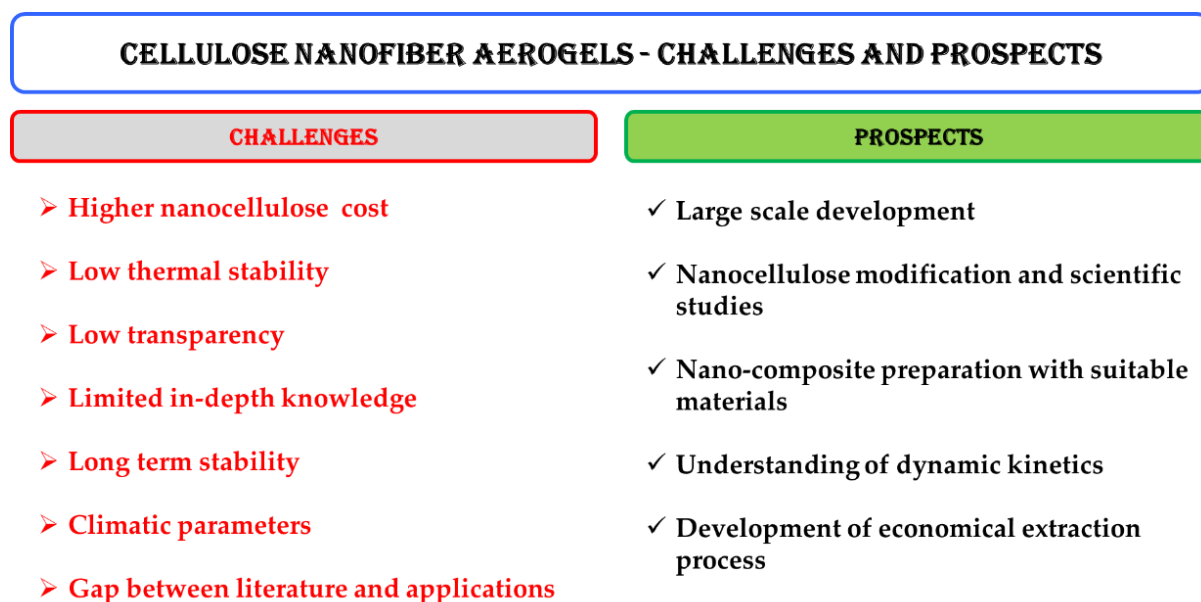


Fig. 15. The summary of the future outlook of nanocellulose aerogels in solar applications.

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Model	Concept	Equation	Advantage	Disadvantage	Reference
Conceptual	Amount of radiation passed through the aerogel is an exponential function of thickness of the aerogel.	$k_g \frac{T_{g,i} - T_{g,o}}{L_g} = h(T_{g,o} - T_{amb}) + \sigma \varepsilon_g (T_{g,o}^4 - T_{amb}^4)$	<ul style="list-style-type: none"> • Ideal case • Less expensive 	<ul style="list-style-type: none"> • Not Realistic 	[120]
Detailed	Radiation intensity inside the aerogel is decreased due to absorption, out scattering and increased due to thermal expansion, in scattering.	$\cos \theta \frac{dI_{\Omega}}{dz} = -(\kappa + S)I_{\Omega} + KI_b + \frac{S}{4\pi} \int_{4\pi} \Phi_{\Omega \rightarrow \Omega'} I_{\Omega'} d\Omega'$	<ul style="list-style-type: none"> • Accurate Method • Acceptable availability of computing resources. 	<ul style="list-style-type: none"> • High computational cost. • Reconstruction of real geometry is complex. 	[39]
Rosseland Diffusion	Heat transfer inside the aerogel is considered to be one dimensional.	$\rho c \frac{\partial T}{\partial t} = \frac{\partial q_{cond}}{\partial z} + \frac{\partial q_{rad}}{\partial z}$	<ul style="list-style-type: none"> • Simple • Can be used for optically thick media. 	<ul style="list-style-type: none"> • Limited Accuracy 	[120]
Homogeneous Equivalent	It considers the volume of the absorber as a porous continuum.	$\begin{aligned} \frac{1}{\phi} \frac{\partial(\rho_f v_D)}{\partial t} + \frac{1}{\phi^2} \nabla(\rho_f v_D v_D) \\ = -\nabla(P)_f^f + \frac{\mu_f}{\phi} \nabla^2 v_D \\ - \left[\frac{\mu_f}{K_1} - \frac{\rho_f}{K_2} v_D \right] v_D \end{aligned}$	<ul style="list-style-type: none"> • Less time consuming. 	<ul style="list-style-type: none"> • Limited Accuracy. • Selection of appropriate empirical terms is difficult. 	[121]

Table 2 Modelling strategies adopted for porous structures in solar thermal receiver.

Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: