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Review Article

Heat enhancement in solar flat plate collectors – A review

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ABSTRACT

This article provides an overview of recent advancements in the design and performance of flat plate solar collectors (FPSCs) for solar thermal power plants. The article highlights various strategies that have been explored to improve the efficiency of FPSCs, including the use of Micro Heat pipe Arrays, nano-materials, phase change materials, and novel tube geometries. The study emphasizes the importance of keeping costs low while improving overall collector efficiency and highlights the research gap in distinct aspects of FPSCs for heat enhancement. The article concludes that these advancements have the potential to significantly increase the use of solar thermal power, which could play a critical role in reducing our dependence on fossil fuels and mitigating climate change. This study examines the power potential and carbon emission reduction capabilities of solar collectors in India, taking into account the local climatic conditions and geographical location. The study also identifies major challenges and opportunities in the current research domain. Based on the analysis, the study highlights the opportunities for commercializing low cost solar plants in India.

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INTRODUCTION

The primary energy source that traverses the atmosphere and ultimately reaches the surface of the Earth is none other than the sun. Among all renewable resources, solar energy is the most readily available and constitutes the vast majority of the sun's radiation that reaches our planet's surface [1]. This is an encouraging fact in a world where energy demand is increasing, and the effects of global warming, which are exacerbated by the use of non-renewable and highly polluting fossil fuels, are wreaking havoc on the planet, intensifying the crisis [2].

Solar flat plate collectors, which utilize the sun as a source, generate heat. Solar radiation is captured and transformed into thermal energy, which is used for various purposes. The type of solar collectors are shown in Figure 1 [3]. The working fluid, such as air or a fluid, then receives this energy. By converting infra-red radiation into heat energy, typically utilizing water as the operating fluid, the collector facilitates the process [4]. Sunlight penetrates

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the glass covering of the collector and is absorbed by the absorber plate, which heats up as a result. From here, the heat is transferred via conduction at the point of contact of absorber tubes mounted above or beneath the absorber plate. Through convection, the heat is then transported to the working fluid flowing through these pipes, which exits the collector via the outlet and flows into a storage tank [5]. This hot fluid, which attains sufficiently high temperatures to change phase into a vapor form, may be utilized to generate electricity by means of a turbine. As demonstrated by Werner P. [6], this process is utilized for solar thermal power plants to generate electricity as part of a hybrid system in conjunction with photovoltaic solar panels, particularly during periods of no direct irradiation from the sun.

Solar energy and solar radiation have been utilized since the dawn of civilization. Initially, they were mainly used for drying clothes or other household items, but significant advancements have been made since the 1700s. De Saussure invented the precursor of the contemporary solar collector in 1767. He constructed an insulated box with three layers of glass on top to capture the sun's energy [7]. This technology has been refined and developed over the years, and commercialization and widespread installation of flat collectors began worldwide in the 1930s, even though Fred Brooks first presented the actual theoretical description of flat plate collector properties in 1936 [8].

Solar collectors can be categorized based on the manner in which they transfer solar radiation from the absorber plate to the working fluid. This classification can be further segregated based on the degree of thermal enhancement achievable through specialized components, leading to non-concentrating collectors with low temperature requirements, suitable for domestic applications, and concentrating collectors that generate high temperatures

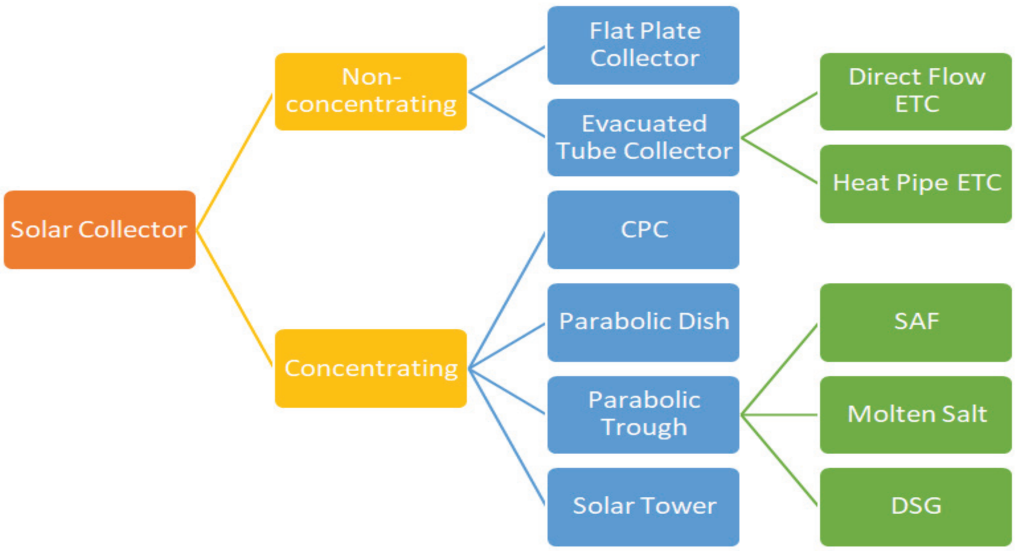

Figure 1. Types of solar collectors.

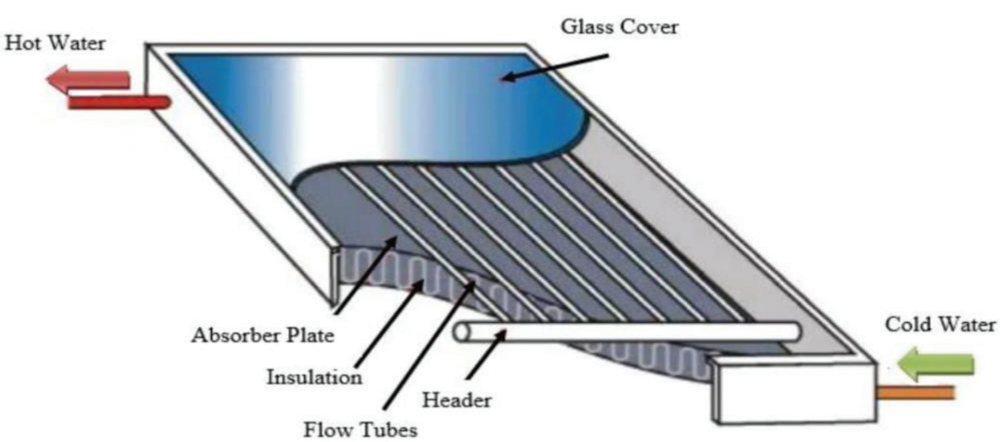

Figure 2: Parts of a flat plate solar collector [From Alam T et al. [10], with permission from MDPI**].**

and even electricity. Among the concentrating solar collectors, the parabolic dish and trough have been extensively studied and deployed. Conversely, the evacuated absorber tube is the most widely researched and employed among the non-concentrating solar collectors. The flat plate variant of solar collectors, owing to its straightforward design and ease of deployment, enjoys widespread adoption globally [9].

A flat plate solar collector (FPSC) typically includes an insulated casing, absorber plate with glazing, tubes, cover strip, and thermal insulation which is shown in Figure 2. Since FPSCs are usually installed on a roof or open field and not movable, they do not require a sun tracking system. In the Northern Hemisphere, the absorber plate should ideally face south, and in the Southern Hemisphere, it should face north to optimize performance [11]. The receiver plate should be inclined at an angle equal to the latitude of the installation site, with minor adjustments of 10-15° based on the specific application. Various types of solar collectors have been evaluated for their efficiency over time and are depicted in Figure 3, which shows their maximum operating temperatures and corresponding thermal efficiencies. The flat plate collector is a popular choice due to its simplicity and versatility [12].

Although the design and structure of the plate has existed with minimal changes over the decades, and is the most commonly utilized solar panel type for water heating applications in the household and similar levels, there are a plethora of minor and major changes in design and manufacturing from collector to collector. Material selection and design considerations can have a significant impact on both thermal-based output and reliability according to its use in different situational circumstances [13]. Here is a brief explanation of the components making up a common FPSC:

An absorber or receiver plate is essentially a quadrilateral thin slab of material with a greater thermal conductivity, particularly copper or aluminium due to their high thermal conductivity. To acquire the most solar radiation absorption, it is typically covered with absorptive material and painted black. This thin layer is fairly permeable to long-wave solar energy yet extremely absorbent to short-wave solar radiation. There is another thin layer with greater reflectivity towards radiation around the infra-red section of the electromagnetic spectrum underneath the previous coating. The receiver plate collects thermal energy expelled by the sun, then transfers it through to the absorbing fluid with the least amount of heat loss [14,15].

Present on the underside and the upper surface of the absorption plate are large diameter tubes for liquid entry and exit. The manifold is made of copper to maximize heat dissipation from the absorber plate. These headers are connected to copper pipes by welding. An aluminium sheet is covered with a substance which has an exemplary effect on the absorption of solar radiation and its consequent availability as heat energy that can be utilized by the collector. The absorber plate is attached to the riser pipes, generally made of Copper, using the technique of Ultrasonic welding, and henceforth the assembly is heat-treated to increase its strength [16].

On the absorber plate, several copper tubes are arranged parallel to each other. Through these tubes, the chosen absorber fluid flows to receive heat via convection. Both ends of the liquid pipe are connected with an end pipe of greater diameter. They are attached to the copper plate

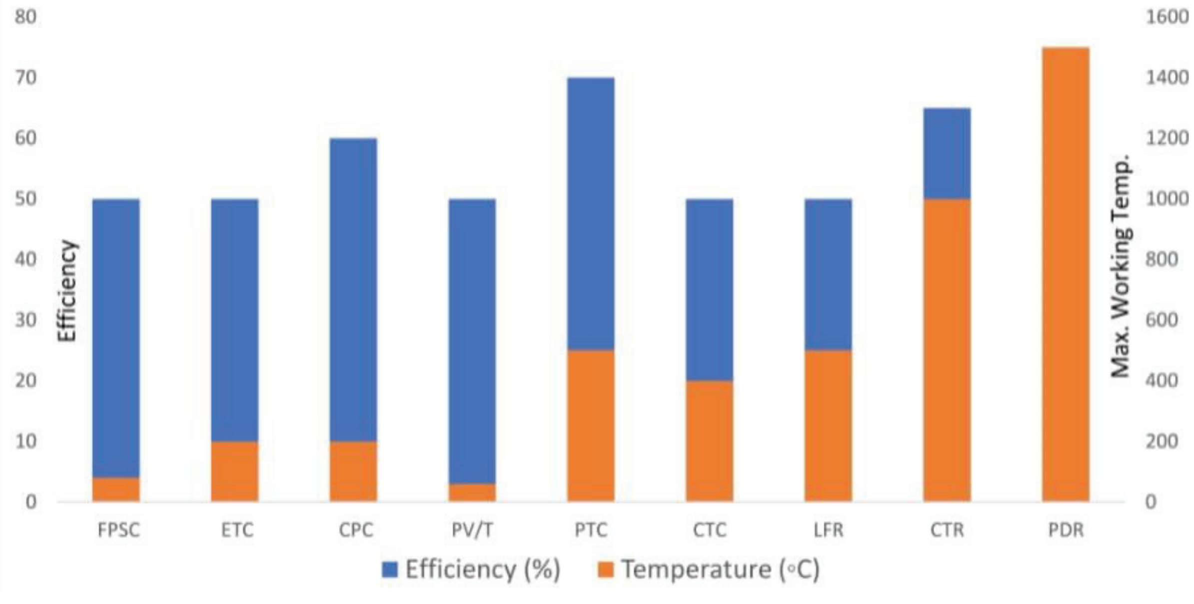

Figure 3. Types of solar collectors VS efficiency [From Alam T et al. [10], with permission from MDPI].

securely via soldering for maximum surface contact and therefore smooth heat transfer between them [17].

The absorber plate's capabilities may also benefit from application of a thin glaze of a material that has emissive properties, including plastic or glass. A flat plate collector has one, two or more glazing layers on top of a black absorbing sheet. Glass containing low amounts of iron is primarily utilized for purposes like glazing, with increased ultraviolet ray (high frequency on the electromagnetic spectrum) transmission and little or no radio wave (low frequency on the spectrum) transmission. Glazing is generally used as a protective layer for the entire inner setup of the solar collector due to its high transmissivity, as it allows through most wavelengths of solar radiation and thus insulates the absorbing panels from their surroundings by confining the radiation and reducing both convective and radiative losses. Transmittance of shortwave radiation can also be improved with anti-reflection coatings and surface finishes. Glass material does not absorb heat like absorbent panels [18].

Thermal insulation will be applied at the surface of the inner sides as well as the lower surface of the FPSC, leading to reduced loss of heat. Various insulation materials such as mineral wool, rockwool, and styrofoam are used for this. Insulation reduces heat loss from absorbing panels and helps heat pipes and panels [19]. A multitude of designs and working methods are being actively researched for modifying FPSC thermal applications, like panels with insulation via vacuum or by filling them with gas. In the first method, the gap between the cover lip and the receiver plate is filled with a vacuum which results in a decrease in conduction and convection losses. This was first conceptualized in 1892 by Sir J. Dewar, with an experiment where two pistons were placed in each other with the junction at the neck and the gap between the pistons occupied by vacuum. The environment created thus within the pistons reduced almost the entirety of the conductive and convective heat transfer [20].

The various components are held together in place using a casing of either wood or steel. An insulating layer is provided on the bottom of the housing. Then comes the absorber plate, which has copper pipes built into it. The sides are also insulated to reduce heat loss through convection. Finally, a transparent plate made of glass is added over the absorber plate to create a continuous pocket of air separating, it from the rest of the surrounding atmosphere. Each structural component is properly fitted and attached via machine processes to increase contact surface area and thus enable optimum transfer of heat. Housings protect components from environmental influences such as dust, precipitation and moisture [21]. The use of a reflector to concentrate radiation onto the absorber plate was also highly effective, in that there was an increase in solar collector efficiency from 51%, without a reflector, to 61% with a reflector, an almost 10% increase [22].

Oscillatory flows in absorber tubes within a solar collector to create a thermal pumping system to transfer heat from the collector to a reservoir is a promising development in efficiency enhancement for solar applications. Upon investigating thermal behaviour of the fluid using Newtonian models, it was found that the effective diffusivity was greater than the molecular diffusivity of the fluid. Furthermore, the use of oscillating viscoelastic fluids gave rise to resonance frequencies for which thermal diffusivity show maxima values several magnitudes greater than those for Newtonian fluids. Thus tuning at resonant frequency enhances heat removal during the pumping process without net transfer of mass, and reduce heat loss to the environment. For such promising preliminary results, experiments with more practical conditions must be considered for further development [23].

From a survey of existing literature, it was found that every aspect and component of a solar collector can be optimized to provide a substantial improvement in collector performance. Table. 1 summarises the significant works carried out on different parts of the system in the past. This includes painting of the absorber plate black to decrease reflection of any wavelength [31], and as a more advanced method, spectral coatings of various materials that have optical properties that, when used by themselves or as part of specific alloys, can provide maximum absorption to ensure that the highest percentage of radiation is available to the working fluid [32]. Theoretically, for maximum effectiveness, the coating must have a sharp cut-off in maximum absorptivity before the wavelength that is a compromise between the ability to absorb solar radiation, and the radiative heat losses through the coating. Essentially, the coating acts as a filter to allow in as much short-wave radiation as possible, while keeping emittance low. Practically, this sharpness is not achievable yet can be approached with the use of certain materials for specific temperature ranges of the collectors [33]. For both high and low temperature applications, dielectric-metal-dielectrics (DMD) are generally more cost effective than other types of selective coatings for their relative effectiveness and thus many studies are being done on DMD specifically to improve the optical properties of the materials [34].

The absorber plate itself can also be improved with it having rough surfaces and consisting of sheets with micro heatpipe arrays which increase heat transfer by virtue of more contact surface area and greater heat removability respectively [35-37]. Additionally, the usage of phase change materials reports a significant increase in collector efficiency even during non-sunlight hours. This is due to their defining characteristic where energy is absorbed for a phase change, and in turn released at a later time when the phase is reverted. This delayed energy release is particularly useful for situations where there is not enough solar radiation coverage for the energy required [38]. The following section explains the works carried out to enhance the collector efficiency and thereby the overall efficiency too.

Table 1. Summary and inference of different parts of solar collector

Parameters focused	Methodology adopted	Inference from result	Reference
Flat plate solar collector design	Review of advancements in designs of FPSCs in recent years	Absorber plates with black paint coating performed better than other colors due to the black having the highest absorptivity of solar wavelengths. Selective spectral coatings of high transmittance made with transparent conductive oxides - layers of zinc oxide doped with aluminum and indium oxide doped with tin - did not increase performance in collectors with single glazed highly selective absorbers, but seem promising for use in those with single-glaze low selective absorbers and double-glaze high selective absorbers. Optimal air gap thickness between glass and absorber plate is 10mm. This was discovered experimentally, as a greater gap would not allow the maximum accumulation of heat due to the scattering of radiation, and a smaller gap would not facilitate the greenhouse effect that many solar flat plate collectors depend on.	[24]
Solar flat plate air collector design	Overview of design modifications in FPSACs	Rough absorber plate surface results in higher convective heat transfer coefficient, as there is greater contact surface area as well as contact time duration between the absorber plate and the working fluid. Collectors using PCM in the absorber sheet have extended working time, since the phase change material stores the absorbed energy until it is time to release it during phase transition, giving a 13%-20% collector efficiency increase, while also increasing the ambient air temperature by 10-16 degrees.	[25]
FPSC performance	Review design modifications in FPSCs	Various coatings can increase solar absorptivity and decrease emittance, like a black nickel-cobalt coating which increases absorbance to 0.948 while being environmentally agreeable. Nanofluids improve thermal efficiency by virtue of the highly conductive metals being used as the nano particles, like a mix of Al2O3 and CuO in water with a pH of 3 boosting collector efficiency by 52%. Mini/macro channels improve surface contact area and heat transfer, and thus efficiency upto 73% with aluminum fns and 66% with wickless heat pipe at a low flow rate. However, design is very complex and choking of the channel is a major issue. Vacuum in collector can decrease convection losses around absorber and enable high conversion efficiency above 70%.	[26]
Design of solar collector	Overview of FPSC design modifications	Modifications included increasing the number of liquid passages and this time duration of contact between working fluid and absorber plate, corrugating and roughening the absorber plate to increase contact surface area, adding an additional cover plate to decrease thermal losses, using photovoltaic/thermal (PV/T) panels, and using phase change materials, to improve collector efficiency.	[27]
Thickness of absorber plate in solar flat plate collector	3D numerical simulation	Favorable thickness of absorber plate is 0.01m at all times of the day compared to 0.005 and 0.015 by experimental analysis, which is a middle ground over too thin to prevent the loss of short-wave radiation back into the atmosphere, and too thick to allow maximum radiation into the air gap between the glazing and the absorber plate.	[28] & [29]
Glazing with selective spectral coating	Review of advancements in various types of selective coatings for solar collectors	A very promising DMD composition MgO/Zr/MgO, which exhibits a solar absorptivity of 0.918 with a thermal emittance of 0.10 and can be used for low temperature applications such as those seen in FPSCs.	[30]

CHARACTERISTICS OF SOLAR FLAT PLATE COLLECTOR

From the Law of Heat Conduction given by Fourier,

$$Q = -kA_{cond}\frac{dT}{dx} \quad (1)$$

Thus it can be seen that the magnitude of heat transfer that occurs undergoes changes that are a direct function of contact area. From this we can conclude that by increasing the area directly attached to the absorber tubes and the receiver plate of the collector, we increase the amount of heat available to the tubes and make that heat available to the utilizing fluid [39].

Also, from Newton's Law of Cooling

$$Q = hA_{conv}dT \quad (2)$$

Thermal energy can be transferred by the flow of the fluid flowing through the pipes, while the fluid's heat storage capacity determines how much heat energy can be extracted and used. These formulae are general and can be used for all components of the solar collector that involve heat transfer, and thus are not applicable for sections such as the calculation of optimum tilt angle.

When sun radiations incident on absorber plate, the amount of radiation absorbed is given by [40],

$$Q_i = I(\tau\alpha).A_{rad} \quad (3)$$

The heat lost to the environment from the collector due to it having higher temperature than surroundings is [41]

$$Q_o = UA(Tc - Ta) \quad (4)$$

So the available temperature for convection through fluid is given by

$$Q_u = Q_i - Q_o = I\tau\alpha.A - UA(Tc - Ta) \quad (5)$$

The heat carried by the flowing fluid is given by,

$$Q_u = mC_p(T_o - T_i) \quad (6)$$

Now, the heat removal factor for a collector can be calculated as [42]

$$F_R = \frac{mCp(T_o - T_i)}{A[I\tau\alpha - U(T_i - T_a)]} \quad (7)$$

The collector will gain maximum usable energy when the fluid is at inlet, and is given by the Hottel-Whillier-Bliss equation:

$$Q_u = F_R.A[I\tau\alpha - U(Tc - Ta)] \quad (8)$$

The performance of the FPSC, also known as the efficiency of the collector, can be said to be the ratio of useable energy gained by the collector by the overall incident solar radiation [43].

$$\eta = \frac{\int Qudt}{A\int Idt} \quad (9)$$

Thus, the efficiency of the solar collector is proportional to the usable thermal energy 'Q_u', and inversely dependent on the working area of the collector 'A' and intensity of solar radiation incident on the collector 'I'. Hence, we can infer that one of the best ways to enhance the instantaneous efficiency of any FPSC of a given size and with the amount of incident solar radiation for the given time of year and location, is by increasing the usable heat available in the collector. This aspect of the collector is mainly dependent on the contact surface area of the interfaces of various components, namely, that of the absorber plate and the outer surface of the fluid tubes (conduction), as well as that of the fluid tube and working fluid flowing within (convection). As a result, one of the ways to improve this property of a collector is by modifying the tube geometry to attain a shape with greater contact surface area with the collector plate than the conventional circular tube.

While available incident solar radiation cannot be controlled, the absorption of this radiation can be maximized by increasing the absorptivity of the collector by using special coatings, changing tilt angle, or other methods of concentrating the radiation onto the absorber component.

Size and surface area of the collector can also be modified according to the requirements and conditions of the solar collector system to be installed.

Methods to Enhance Collector Efficiency

Flat plate collectors increase collector efficiency in a number of ways, including changing the tilt angle, using phase change materials, nano-materials, temperature sensors, changing the shape of the collector plate, and changing the shape of the liquid pipe [44]. As it is known, the amount of solar radiation incident on the surface of the Earth is not the same throughout the day. The angle at which the radiation hits the surface changes with time from morning to evening. One way is to change the inclination of the solar panel to the surface of the earth over time so that the incoming radiation he always has maximum radiation throughout the day [45]. Also, to change the tilt, you could use a temperature sensor that basically detects radiation and converts it into an electrical signal, which you send to an electric motor to move the collector. Water is considered one of the default options for the fluid flowing through the absorber pipes. Some characteristics that affect optimal absorption from the collector include the flow of fluid, coatings or films that are semi-permeable on the open side of the receiver plate, loss of thermal energy due to convective and radiative heat transfer, and the absorption capacity, particularly pertaining to the surface.

The usage of PCM is very pertinent to this purpose of increasing overall collector efficiency, as they not only improve the working of the solar collector, but also release stored energy on a slightly delayed timescale during a phase change, which is invaluable for times of expected or unexpected lack of adequate levels of intensity of solar radiation. Phase change materials are generally used in within the absorber plate itself or as an envelope for the tubes carrying the working fluid. For example, paraffin wax can be used inside the absorber sheet to increase the ambient temperature by as much as 4 degrees and increase the collector's efficiency by almost 50% due to its energy storage and release capabilities.

Solar Radiation Incident on the Collector

The works related to tilt angle variation are summarised in Table 2. It is found that the majority of the works focus on maximizing incident solar radiation on the FPSC by the optimization of the angle at which the collector is facing the sun, depending on the specific geographical location as well as time of year. Some also study the various models

Table 2. Summary and Inference of tilt angle optimization in solar collector

Parameters focused	Methodology adopted	Inference from result	Reference
FPSC inclination angle	Calculation of total incident solar radiation at various tilt angles.	Collector energy loss is approximately 1% if tilt is adjusted seasonally to optimum angle as compared to a monthly adjustment, thus saving on cost. Thus, close to maximum solar radiation is incident upon the solar collector surface at any given time of year.	[46]
FPSC inclination angle	Study of radiation from the sun incident on collector plate at different tilt angle, time, day, and latitude.	Optimal inclination of FPSC is affected by time, day, surface orientation, latitude, and declination. This is due to the inclination of the earth on its axis as it revolves around the sun causing the solar radiation to vary in incident angle and intensity with respect to the mentioned parameters.	[47]
FPSC inclination angle	Conduction of thermal experiments for each part of the thermal collector and determination of effect of tilt angle of absorber plate.	A plate with inclination almost perpendicular to incident radiation had higher absorption of solar radiation. Here, solar radiation has zero to very small value of incident angle which means that instead of a slant, the rays arrive head on to the solar collector surface and can thus be absorbed fully.	[48]
Empirical models of solar flat plate collector	Comparing empirical models for estimating monthly global solar at a geographical location	3 global solar radiation models were compared using statistical methods - the coefficient of determination (R2), the root mean square error (RMSE), the mean bias error (MBE) and the t-statistic) to determine which sunshine-based model was best suited for the region of Nigde, Turkey.	[49]
FPSC tilt angle optimization	Mathematical and experimental analysis of optimum tilt angle of FPSC.	Inclination of plate is to be changed monthly in the range of 0-56 degrees annually in the selected geographical area. Statistical analyses show that mathematical models involving latitude and declination have usable applications in the geographical area around the Western section of the Himalayas.	[50]
Declination dependence and comparisons of 3 solar models	Experimental analysis of 3 solar models and determination of declination dependence	For a certain absorbed solar radiation amount, tilting FPSC at an optimum angle results in smaller required area and thus costs are reduced. Optimum tilt angle $\beta = \varphi - \delta$ regardless of location or season, and is zero for negative results.	[51]
Tilt angle of solar collector	The efficiency is measured at different tilt angle and compared	In winter, fixed winter angle captures 81-88% radiation as optimum tracking, 74% in spring and autumn, and 68-74% in summer. Optimum tilt angle in India in June is 0 as indicated by all models (Lin & Jordan, Rekindle, Hay, Badescu) Compared to solar thermal systems, photovoltaic systems are more sensitive to optimum inclination as well as azimuth angle.	[52]
Tilt angle of solar thermal collector systems	Experimental analysis of different tilt angle effects on solar collector heat absorption	Collector plates are customarily oriented towards the equation in each hemisphere in order to facilitate maximum amount of solar radiation incident normally upon the FPSC, due to the nature of the Earth's tilt on its axis. Optimum tilt angle in Turkey in July is 1, and in December is 65, which clearly shows that the optimum tilt angle changes monthly according to the orientation of the Erath with respect to the sun.	[53]

used in calculations for incident solar radiation with varying parameters.

Geometry of the Collector

It is observed that the shape of the collector plate changes. This method can improve efficiency by at least 2%. The most studied and successful geometry is the rhombus.

As discussed earlier the collector plate geometry plays a vital role in improvising the efficiency of the collector. In past studies it is observed that the geometric modifications such as usage of rhombic and square collectors increases the efficiency by at least 2%. The notable works where the collector geometries are modified is summarized in Table 3

Usage of Phase Change Materials

A particular substance called a Phase Change Material has the capability of absorbing and releasing heat as a result of it undergoing a phase change (among solid, liquid, and gaseous), and this allows for it to exhibit a heating or cooling effect as needed. This heat transfer occurs during changes in the material upon absorption or release of sufficient energy according to its latent heat in order to melt, condense, or vaporize it [57]. Some examples of phase change materials include paraffins [58], Tritriacontane, Erythritol [59], etc., the studies of which are shown in Table 4. These include experiments that demonstrate the property of latent heat storage to improve FPSC performance.

Usage of Nanofluids

Nanofluids involve gases or liquids that contain nanoparticles, which can include nanostructures like carbon nanotubes, graphene flecks, various metals and their oxides, and ceramic particulates, all with sizes at an order of 10^9 m. Some frequently used fluid media are water, oil, and ethylene glycol. These fluids exhibit interesting and, in some cases, properties that are particularly useful in niche fields, including the transfer and storage capacity of heat. This is by comparatively higher thermal coefficients of conduction and convection than as seen in the pure fluid. Some materials that are frequently used in flat plate solar collectors include oxides of metals like Aluminium (AL_2O_3-H_2O), and carbides, which are shown in Table 5, among other studies. The main reason they enjoy more application in this field is due in large part to their suitable density and outstanding increase in thermal conductivity at relatively low costs of production [62].

Table 3. Summary and Inference for collector plate geometry modifications in solar collector

Parameters focused	Methodology adopted	Inference from result	Reference
Geometry of collectors in systems involving heating of water	Experimental comparison of collectors with varying geometrical parameters while having no change in surface area	Using, comparative study of FPSCs having the same working area but different geometrical configuration, is it found that equal sides (square) is more symmetrical and thus easier to manufacture and deisgn, while also giving a slightly better performance than a rectangular collector. Functional equation was derived that can be used to design flat plate collectors.	[54]
Square and rhombic flat plate solar collectors	Experimental and mathematical analysis of the different orientations when shape factor differs	Both geometries considered in experiments give results that show equal tendencies to absorb radiation in the afternoon time, where due to the phenomenon where spread out and scattered radiation in the morning and afternoon are more effective than normal radiation, the rhombic collector tends to give better results than the square as rhombic absorbs radiation at more altitude compare to square and it provides well distributed gravitation force which further leads to better distribution of energy throughout the fluid.	[55]
FPSC connected to a water heater with micro heatpipes	Testing and analysis of heating efficiency as compared against conventional absorber plates	Shortcomings of water pipes in flat plate solar collectors like the high expense while having less than ideal reliability and the many structural damages that tend to occur, can be mitigated using arrays with micro heatpipes. Transfer of thermal energy can be substantially increased by the use of heatpipes that have various inner surface geometries, such as grooves or fins. Thus, the manufacturing expenses remain low but efficiency and working of the overall collector is greatly boosted.	[56]

Table 4. Summary and Inference for phase change materials used in solar collector

Parameters focused	Methodology adopted	Inference from result	Reference
Solar thermal receiver tank with PCM	Testing of the heat storage capability of a hot water receiver tank	Highest thermal efficiency obtained as 54% in the tank in which calcium chloride hexahydrate ($CaCl{\cdot}6H_2O$) as PCM was used, compared to 51% in a standard insulated tank. This is due to the great energy storage capabilities of phase change materials, and reduction in heat losses from the collector system.	[60]
Evacuated tubes with PCM integration with heat pipes	Experimental analysis of solar water heater systems during both normal and high demand operation.	A dual PCM system was used, comprising of Tritriacontane and Erythritol, which demonstrated an overall improvement in functionality of the water heater systems, as well as a 26% improvement in efficiency for normal operations and a 66% improvement for a system in stagnation mode. Both these results are in comparison with solar water heater systems that did not involve PCM. This result is due in large part to the delayed heat release during phase change that PCM is characterized by, which is immensely useful for situations with higher demand and solar radiation intensity is not sufficient.	[61]

Table 5. Summary and Inference for nano fluids used in solar collector

Parameters focused	Methodology adopted	Inference from result	Reference
Nano fluid used with working fluids	Nanofluid-primarily based totally direct absorption sun collector	Thermal conductivity and other liquid thermo-physical parameters are significantly altered when nano-particles are mixed with a liquid nanofluid.	[63]
Working fluids in solar flat plate collectors	3-D computational fluid dynamic model of SFPC	Nanofluids like ones with a 3% solution of Al_2O_3 increase energy harvesting potential, with maximum performance observed at 0.004 kg/s fluid flow-rate.	[64]
Nanofluid-based solar collectors	Characterization of properties that allows for better absorption qualities, like average size, geometry, etc.	Non-concentrating nanofluid-based direct absorption solar collectors improve their results by as much as 15 percent. The substance that constitutes the working fluid does not have a major effect of thermal efficiency, but do gives good results in heat transferred.	[65]
TiO2/ water nanofluid	Experimental comparison of two working fluids (water and TiO2)	Using water as the working fluid, various concentrations of titanium oxide nano-sized particles show varying levels of positive impact on the thermal efficiency of the collector.	[66]

Geometry of Fluid Tubes

Different modifications on FPSC have been studied, namely, variations on number of air passes, types of absorber plates, types of cover plate, and use of PCM (phase change material) [67]. Experiments carried out are described in Table 6, which show that the geometries of fluid tubes play a significant role in the thermal efficiency of the FPSC. Novel geometries that could prove beneficial to heat enhancement include tubes with semi-circular [68], isosceles triangle [69], and trapezoid cross sections [70].

Research Gap

The improvement in the working of a FPSC as a result of optimizing fluid tube cross sectional geometry is comparable to that arising from the various modifications and additions to the other components of a standard collector. There is an advantage in that these changes are far easier to implement to a collector model and do not require any additional upkeep than already needed for the conventional tube.

Very little research has been done on fluid tube geometry, and usually circular and inverted triangular were

Table 6. Summary and Inference for change in fluid tube geometry in solar collector

Parameters focused	Methodology adopted	Inference from result	Reference
FPSC with triangular geometry of receiver tubes	Triangular collector analysis using computational fluid dynamics software	Triangular tube configuration increases the temperature output by the collector due to higher area of contact between the surface of the tube and the plate.	[71]
Geometry of absorber tube	General overview and review of advancements on absorber tube geometry in FPCs	Mass flow rate in a FPSC has a direct and visible effect on its efficiency, which can be maximized by the usage of tubes with a triangular cross-section, even when compared to other novel geometries of cross-section like circular, square, and elliptical. Reducing area of the collector while increasing diameter of the tube by reducing raiser length increases performance of the collector. Sandwich type collector gives a good level of efficiency while being inexpensive and easy to manufacture. Absorber with trapezoidal profile of plate gives optimal efficiency.	[72]
Inner grooved copper absorber tube	Test setup with different inlet temperatures and mass flow rates	Overall increase in instantaneous efficiency with inner grooved copper tube is 5%, implying that surface area is directly proportional to outlet temperature.	[73]
Circular, semi-circular and elliptical cross sections of collector tube	Numerical modeling and CFD analysis	Different flat plate collector tube cross sections showed that the best working performance occurred for tubes with a circular cross-section, giving outlet liquid temperature of 330K and efficiency of 68%, compared to 51% for semicircular and 60% for elliptical. Circular cross-section gave minimal pressure and velocity differential. However, semicircular cross section had better uniformity of the distribution of temperature at the outlet of the pipe.	[74]
Square and triangular riser tubes cross sections in heating water using an FPSC	Different thermal fluxes compared using ANSYS CFD models	Square and triangular riser tube configurations give the highest values of temperature for water as the output when compared to those with a geometry of circular cross-sections. Rise in efficiency is about 8-10%	[75]

studied. While more complex geometries have been analyzed, it has been seen that a substantial boost in FPSC performance can be achieved with the simpler modifications, as long as the area of contact between the absorber plate and the fluid tube is maximized. Thus, a relatively simple cross section for ease of manufacture is more feasible for attaining the same levels of heat enhancement as the more complex modifications.

Global Trends in Solar Thermal Technology

From a survey of studies being published in recent years, a steady decline for total papers published in this time period is evident, from which one can infer that a) while significant research gaps exist, there is not as much interest in areas pertaining to solar thermal collectors as there evidently was almost a decade ago, or b) due to the widespread commercial use [76] and thus establishment of solar thermal collectors, as shown in Table 7, there is not as much interest in pioneering in solar collector technology at it may not result in mass production due to the costs of overhauling as existing system. This also contrasts the fact that usage of solar thermal collectors across the globe is at an all-time high [77].

It has been observed that the most, if any, of the adverse environmental effects from installation and operation of solar power generation systems are applicable for photovoltaic setups rather than solar thermal ones [78], due to hazards involved in the manufacturing of materials for PV cells, which can also release toxic materials into the atmosphere [79].

Feasibility Study of Implementing Solar Technologies in India

Areas at or near the equator are particularly viable for energy generation via solar sources due to the abundance of solar energy and, especially in India, the large swaths of land available for the construction of solar power plants [80]. These plants can provide environmentally friendly and

Table 7. Applications of solar collector types

Applications	Type of collectors used
Solar water heating	
Thermosyphon system	FPC
Integrated collector storage	CPC
Direct circulation	FPC, CPC, ETC
Indirect water heating system	FPC, CPC, ETC
Air system	FPC
Space heating and cooling	
Space heating and service hot water	FPC, CPC, ETC
Air system	FPC
Water systems	FPC, CPC, ETC
Heat pump systems	FPC, CPC, ETC
Absorption systems	FPC, CPC, ETC
Adsorption cooling	FPC, CPC, ETC
Mechanical systems	PDR
Solar refrigeration	
Adsorption units	FPC, CPC, ETC

minimally intrusive installations that can provide much-needed electrical resources for use in rural and remote locations [81], providing a better long-term outcome than the establishment of conventional power generation plants that emit harmful byproducts [82] and lead to declining health in local populations, in addition to the existing contributions to global warming [83] and climate change [84].

As shown in Table 8, data collected regarding the solar energy generated all across India prove that the normalization [85] and usage of clean energy sources by the general public is steadily increasing which is shown in detail in Figure 4. This further cements the need for more research to be done in the pursuit of easily attainable and feasible methods of utilizing solar energy for daily life.

Trends across India in recent years demonstrate the increasing popularity of solar sources of energy, particularly in regions of higher average solar radiation.

There is great scope for enhancing the performance of a FPSC particularly in areas studying the use of nanofluids within the absorber tubes, use of PCM and evacuated tubes, implementation of collector tilt angle mechanisms,

Table 8. Solar energy generation (MW) state-wise in India through years 2017-2021 [86]88]

Year	2017	2018	2019	2020	2021
States					
Andhra Pradesh	1867.23	2195.46	3085.68	3610.02	4203
Arunachal Pradesh	0.27	5.39	5.39	5.61	5.61
Assam	11.78	12.45	22.4	41.23	42.99
Bihar	108.52	142.45	142.45	151.57	159.51
Chhattisgarh	128.86	231.35	231.35	231.35	252.48
Goa	0.71	0.91	3.92	4.78	7.44
Gujarat	1249.37	1588	2440.13	2948.37	4430.82
Haryana	81.4	216.85	224.52	252.14	407.83
Himachal Pradesh	0.73	0.73	22.68	32.93	42.73
Jharkhand	23.27	25.67	34.95	38.4	52.06
Karnataka	1027.84	4944.12	6095.56	7277.93	7355.17
Kerala	74.2	107.94	138.59	142.23	257
Madhya Pradesh	857.04	1305.35	1840.16	2258.46	2463.22
Maharashtra	452.37	1239.18	1633.54	1801.8	2289.97
Manipur	0.03	0.06	3.44	5.16	6.36
Meghalaya	0.01	0.02	0.12	0.12	0.12
Mizoram	0.1	0.2	0.5	1.52	1.53
Nagaland	0.5	1	1	1	1
Odisha	79.42	79.57	394.73	397.84	401.72
Punjab	793.95	905.62	905.62	947.1	959.5
Rajasthan	1812.93	2332.77	3226.79	5137.91	5732.58
Sikkim	0	0	0.01	0.07	0.07
Tamil Nadu	1691.83	1908.57	2575.22	3915.88	4475.21
Telangana	1286.98	3291.25	3592.09	3620.75	3953.12
Tripura	5.09	5.09	5.09	9.41	9.41
Uttarakhand	0	0	0	0	0
Uttar Pradesh	336.73	694.41	960.1	1095.1	1712.5
West Bengal	26.14	37.32	75.95	114.46	149.84

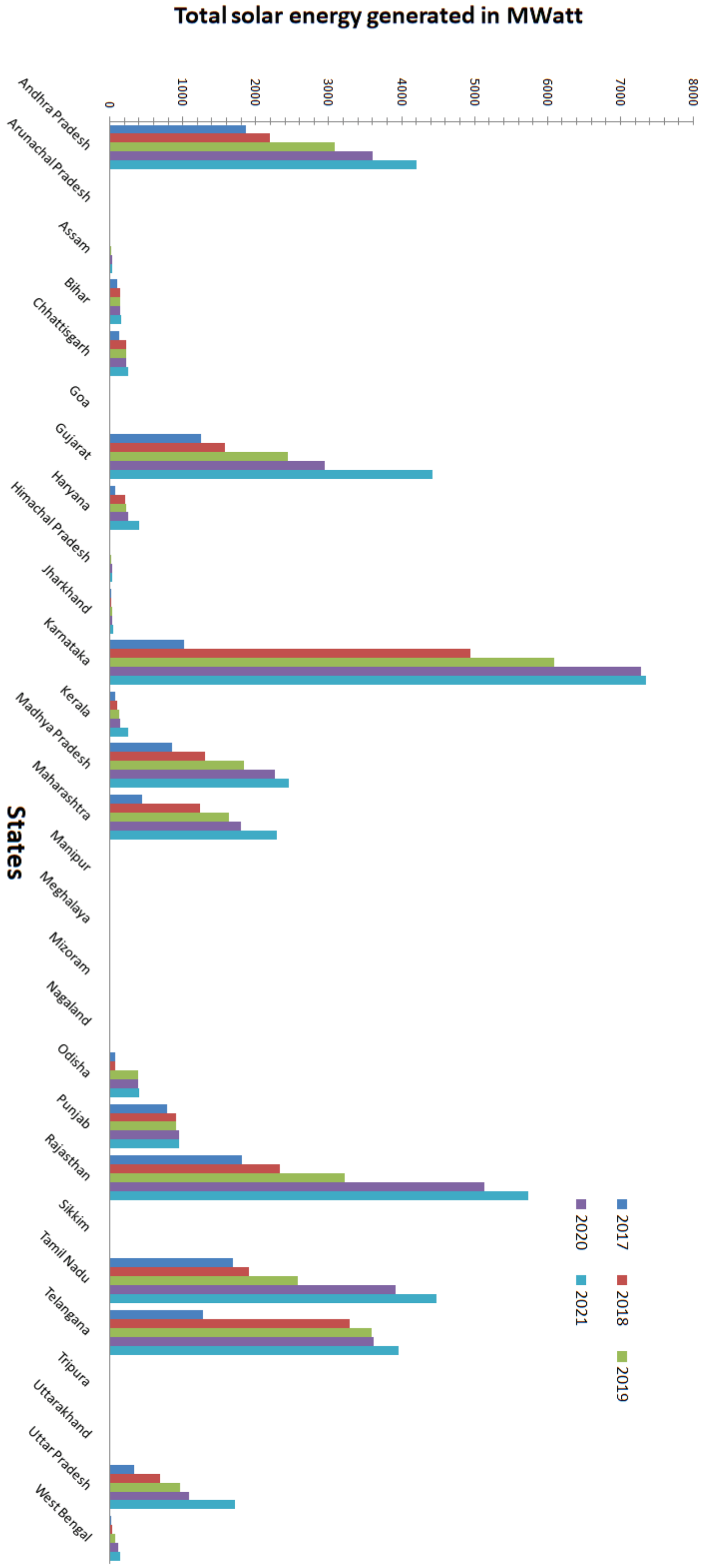

Figure 4. Total solar energy generated state-wise in India through years 2017-2021.

and material optimization. Additionally, upgrading the collector by using various types of concentrators or methods of increasing the intensity of incident radiation have vast avenues for improvement.

OUTCOMES

Constant and steady enhancements made to the basic FPSC can potentially lead to overall improvements in thermal energy devices in general. Research done in this field can have major effects on the way we understand thermal energy and how to utilize it, and thus, any inclination to further the associated technology can accumulate to provide a net advantage. This along with the inevitable rise in popularity of eco-friendly energy sources can propel the human population, with its increasing energy demands, into a bright future.

LIMITATIONS

This study mainly focuses on possible modifications that can be done to a FPSC, which does slightly limit the scope of the findings. However, the inferences from the studies taken can be applied to other types of solar collector, that may have a better baseline efficiency than a FPSC initially. Since solar thermal collectors do operate on similar bases of working principle, the design modifications for a FPSC are mostly transferrable. For example, some aspects, such as tilt angle, as less relevant for trough collectors, but can still provide some improvements, albeit to a lesser extent, for other types like the parabolic dish collector.

Thus more in-depth research specific to each type of solar thermal collector is needed for the enhancement of their respective performances, which this study does not tackle.

CONCLUSION

Different modifications on flat plate solar collector have been studied, including tilt angle of the FPSC, collector plate geometry and other modifications, use of nano-materials and PCMs.

- Coatings like black nickel-cobalt have been used to increase absorptivity of the glazing layer to 0.948 while remaining environmentally safe, as well as selectively transmissible, as well as MgO/Zr/MgO, which exhibits a solar absorptivity of 0.918 with a thermal emittance of 0.10. Optical improvements are still being researched in this field, and further developments can provide widely useful.
- The use of micro heatpipes or phase change materials like paraffin wax in the absorber plate to increase collector working time, as well as the integration of phase change materials like Tritriacontane and Erythritol with the fluid pipes of the collector to utilize their energy storage and release at a delayed time for use during non-sunlight hours.
- A major area for improvement is in the geometry of the absorber pipes themselves, to increase the contact surface area and thus enhance the heat transfer between the collector plate and the fluid tubes. Relatively little research has been done on fluid tube geometry, and even then they do not compare the novel geometries with each other, the most frequently seen being semi-circular, elliptical, trapezoid, and triangular tubes. The triangular cross section shows the most promise with regards to a significant improvement in the heat transfer between the absorber plate, the fluid tubes, and the working fluid within.
- There is also significant scope in areas like nanofluids to improve heat capacity and thus overall maximum temperature output of the FPSC. Unlike photovoltaics, which are far more expensive and difficult to install and maintain, there is great potential for improvement of a technology that enables widespread use of renewable energy, which is especially prudent in this day and age.

NOMENCLATURE

Abbreviations

FPSC	Flat Plate Solar Collector
ETC	Evacuated Tube Collector
CPC	Compound Parabolic collector
PV/T	Photovoltaic/Thermal collector
PTC	Parabolic Trough Collector
CTC	Cylindrical Trough Collector
LFR	Linear Fresnel Receiver
CTR	Central Tower Receiver
PDR	Parabolic Dish Receiver

Greek symbols

β	Optimum tilt angle of a flat plate solar collector
φ	Latitude of the location of the collector
δ	Declination of the sun at that location
α	Plate coefficient of absorption
τ	Glazing coefficient of transmission

English symbols

Q	Heat transfer (W)
k	Conductive heat transfer coefficient, or film coefficient (W/m.K)
h	Convective heat transfer coefficient of the working fluid ($W/m^2.K$)
A_{cond}	Contact area between the surfaces of the two bodies (m^2)
A_{conv}	Area of the interface between the solid surface and flowing fluid (m^2)
A_{rad}	Collector surface area exposed to the sun (m^2)
T	Temperature (K)
T_c	Average temperature of collectors (K)
T_a	Ambient temperature (K)

T_o	Temperature of fluid at the outlet side
T_i	Temperature of fluid at inlet side
x	Length of the solid
I	Intensity of solar radiation (W/m^2)
U	Coefficient of total heat lost by the collector (W/m^2)
C_p	Coefficient of heat at constant pressure (J/kg.K)
F	Heat removal factor
m	Mass flow rate of working fluid

AUTHORSHIP CONTRIBUTIONS

1. Abinicks Raja G.[1]: conceptualization of research, co-writing of paper.
2. Dr. N. Rajamurugu[2]: Conceptualization and Language Editing
3. Pratik R. G[3]: Undertaking research survey, Drafting.
3. Eleena B.[3]: Undertaking research survey, Drafting.
3. Sahil D. B.[3]: Undertaking research survey, Drafting.
4. Dr. M. Sundararaj[4]: Conceptualization and Language Editing

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

The scientific article focuses on an area in the field of research into Flat Plate Solar Collectors that the authors feel has not received enough analysis and experimental verification. While research has been done on the many components of a basic FPSC to retain its simplicity while improving its thermal output and thus its overall performance, the authors of this paper find that the geometry of the absorber tubes within the collector can greatly affect the heat transfer, without the need for additional or complex mechanisms integrated with the collector. Thus, a literature survey of the recent improvements made to a standard FPSC was undertaken, and the summaries and inferences of the scientific articles were elucidated, along with the appropriate citations and references. The paper also analyses the scope of application of FPSCs globally, as well as the feasibility of this technology in India, taking consensus data to analyze the trends over the past 5 years.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript."

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