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A Review of Advancements in the Performance of Solar Water Heaters Using Twist Tape Inserts

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***Abstract:** Solar energy is abundantly available in nature.Solar waterheaters (SWHs) are increasingly recognized as an effective solution for sustainable water heating. However, their thermal efficiency is often limited by suboptimal heat transfer characteristics within the collector tubes.The efficiency of thermal energy conversion is about 70%, whereas the efficiency of direct solar-to-electricity conversion is only 22%. The most promising passive techniques to improve heat transfer are the incorporation of internal inserts, such as twist tape, the application of fins, and the use of vortex generators. This review paper comprehensively analyses recent advancements in the use of twist tape, the application of fins, and the main factors affecting performance, flow efficiency, and the use of directing inserts. This paper provides a summary of work on solar water heating systems with various techniques, including: 1. Economic importance of collector design, 2.Coating of pipes 3.Use of the insertion of twist tape. Different types of heat transfer enhancement techniques have been proposed in this review paper to enhance the performance of solar water heaters.*
***Keywords:** SWH, Efficiency, Twisttape, Review.*

I. INTRODUCTION

Presently, traditional fossil fuels constitute the predominant source of global energy production, and these resources are being used at a concerning pace while simultaneously adverselyaffecting the environment via their emissions. Some estimates indicate that electric power for heating accounts for around 40% of total global energy production. Electricity consumption for heating water in residential, commercial, and industrial environments has been very high. Utilizing appropriate renewable sources for heatingsystems can substantially reduce fossil fuel consumption and significantly decrease energy demand fromconventional sources. In the last four decades (1980-2020), several solar energy systems have been developed via research, demonstration, and extensive marketing. Solar water heating is one of the most prevalent applications of solar thermal technology. Solar water heating is one of the most economically advantageous uses of solar thermal technology. In several locations worldwide, it is already competing on par with systems using alternative energysources. Asubstantial number ofsystems have beenused in India. The majorityofthe Systems use flat plate collectors. The useofsolar water heaters for thermalwater systems is a relativelynovelidea that has achieved globalpopularityduring the last severaldecades. They may be used for manypurposes, spanning fromsmallresidentialto large commercialsectors. The sun’s energy is used to heat water, which is pumped via several suitable collectors. Current solar collectors include flat-plate, evacuated-tube, parabolic-dish, and compound-parabolic collectors, among others. While these collector types vary in design and efficiency, their performance can be significantly influenced by internal modifications that enhance heat absorption and transfer. One such promising approach involves the useof passive techniques, such as twist tape inserts, which are introduced into the flow passages to create turbulence, disrupt the thermal boundary layer, and promote better fluid mixing. These inserts can improve thermal efficiency without requiring additional energy input. Inlight ofthis, this paper reviews recent advancements inthe useoftwist tape inserts, exploring their material selection and effectiveness in enhancing the overall performance of solar water heating systems.

II. ROLE OF TWIST TAPE INSERTSIN PERFORMANCE ENHANCEMENT OF SWHS

Kumar and Prasad (2000) conducted an experimental study on a solar water heater with twisted-tape inserts. Solar water heaters equipped with twisted-tape inserts in the flow tubes perform better than those with flat designs. Heatlosses have been reduced owing to the lower plate temperature, thereby enhancingthermal performance by about 30% compared to conventional flat-plate solar water heaters. Research indicates that twisted-tape collectors have significantly improved performance at lower flow Reynolds numbers (Re≈12,000), beyond which the improvement in thermal efficiency becomes consistent. Research shows that these collectors may exhibit enhanced performance at higher solar radiation intensities [1].

Jaisankar et al. (2008) conducted experimental investigations on tubes equipped with left-right twisted tape inserts in a solar water heater system. The enhanced 30% thermal performance of the twisted tape collector is attributable to the use of swirl flow [2].

Bhaktaet al. (2018)presenteda comprehensive study of the thermal performance of a solar water heater with a nail-type twisted tape inside the copper absorber tube. The maximum useful heat gain, hourly solar energy collected, and hourly solar energy stored in this solar water heater were found to be higher for a smaller nail twist pitch ratio of 4.787. The above parameters peaked at noon and followed variations insolar intensity [3].

García et al. (2017) conducted a comparative experimental investigation on the increase of heat transfer in a flat-plate solar water collector using insert devices. The friction factor increaserelativetothesmoothtube wascalculatedforalldevices. Fi/fsvaluesvariedfrom1.3to79.8,dependinguupontheReynoldsnumberandinsertshape [4].

Rameshetal.(2018)conductedanexperimentalandnumericalinvestigationtoexamine improvement approaches for flat-plate liquid solar collectors, aiming to achieve more compact and efficient designs. V-cuttwistedtapesare increasingtheturbulenceupto 5000. At a flow rate of 144 litres per hour (0.04 kg/sec), the optical efficiency factor increased by 15% and reduced the 30% heatloss.This type of implanted device yields superior results in laminar, transitional, and low-turbulence fluid flow conditions [5].

Karwa and Sharma (2015) reported the first findings from an experimental investigation of a solar water heater using full-width and 75% twisted tapes as heat transfer augmentation mechanisms. The research indicates that the thermal efficiency attributable to twisted tape is enhanced by 4.5-8%, with a greater increase observed with 75% twisted tape [6].

Almeshaal et al.(2020) conductedexperimentsona thermo-syphon solar water heater using a full-length twisted tape, equipped with a rod and spacer at the leading edge, with lengths of 150, 300, and 450 mm, and a tiny twist ratio of 3.The maximum heatlossfrom the rod and spacer for a length of 450mm is 24% and 33%, respectively. Similarly, friction reduction occurs at nearly 53% and 56% respectively [7].

Bora and Bhatt (2020) provided an extensive review of several heat augmentation methods, including heat transfer enhancement using a turbulator, a twisted-tape insert, a wire-coil insert, and a concentric wire-coil insert, to improve the efficiency of solar collectors. An overview of studies conducted by many investigators to enhance the efficiency of solar collectors using different turbulator inserts has been provided. Based on the requirement, a suitable turbulator may be selected to improve the thermal efficiency of the solar collector for industrial use [8].

Chaudharyand Namjoshi (2021) seek to ascertain the impact oftwisted insertion tape height on the efficacy of evacuated tube solar water heaters. At elevated flow rates, the increase in water temperature is quite minimal, primarilybecause the reduced retention time in the collector shortens the heat-absorption period. A significant conclusion of the research is that short-pitch twisted tape produces higher turbulence than long-pitch twisted tape. The increased turbulence enhances heat transfer, leading to a greater increase in water temperature. The primary result of the study is that incorporating twisted tape enhances thermal efficiency, making it a superior heat transfer augmentation method compared to other designs [9].

J. Ananth et al. (2022) examined the effects of a modified double spiral wire heat exchanger with a Kenics insert. Experimentalfindings indicate a reduction in the Nusselt number as the lengths of the rod and spacer increase; concurrently, the flow pressure drop (ΔP) decreases with increased length, in contrast to the complete kenics twist [10].

Puthilibai et al. (2022) used twisted aluminium tubes in their research. The experimental results indicated that the use of twisted tape inserts accelerated heattransfer within the stagnant zone and helped maintain a uniform temperature throughout the tube during the testing phase. The twisted tapes raised the average tube water temperature by up to 11 °C [11].

Patel (2023) developed an innovative solar water heater concept featuring twisted tubes and assessed its thermal performance using K-type thermocouples. The primary objective of the study was to improve the thermal performance of solar water heaters by replacing the circular cross-section with a square one. For the same material of copper and the same length, a square hole with a cross-section of ½ inch is 21% more than a circular hole with a cross-section of ½ inch diameter. Hence, the surface area in the case of a square cross-section is more, so more radiation is incident, thus better temperature results are obtained [12].

Shafieianetal.(2023)conductedareviewofsolarwaterheaters.Theconcentrated variant of solar water heaters surpasses conventional solar heating systems, especially in attaining elevated water temperatures. Their performance is enhancedby a spinning mirror concentrator, with energy efficiency ranging from 63% to 83% in modified SWH [13].

Kiran et al. (2024) examined the performance improvement of a cylindrical parabolic concentratingsolarwaterheater(CPCSWH)by incorporating a twisted-tape insert into the absorber tube. The results may be helpful in the design and optimization of CPCSWHs for diverse applications, such as solar thermal power generation and space heating. Inthe CPCSWH outlet temperature, collector efficiency, and Nusselt numbers are higher with a twist tape insert than without an insert. For a constant water mass flow rate, the outlet temperature and collector efficiency increase with decreasing twist ratio.

When the mass flow rate is fixed at 0.052516 kg/sec, the collector efficiency is 11.35% higher with a twist ratio (Y=1) than with no twist or a plane.

Saravanan et al. (2024) used four separate neural models to assess the performance of a V-trough solar water heater (VTSWH) integrated with square-cut twisted tape (SCTT) and V-cut twisted tape (VCTT). One hundred thirtydatasets were selected for training, and thirty for testing. It was found that the ANFIS model is the most effective of the four strategies studied. The ANFIS model outperformed the other models for the Nusselt number, friction factor, and efficiency, with RMSE values of 0.0805, 0.000363, and 0.4533, respectively [14].

Deshmukhet al. (2025)examinedimprovements in heat transfer, pressure drop, and overall efficiency of solar collectors using a titanium nitride (TiN) nanofluid and twisted-tape inserts. TiN nanoparticles measuring 40–50 nm were suspended in distilled water at volume concentrations of 0.0%, 0.025%, 0.050%, 0.075% and 0.1%. The findings indicate a substantial augmentation in heat transfer efficiency. The experimental results show improved heat transfer performance, with a 475.37% increase in the convective heat transfer coefficient at 0.1% TiN nanofluid concentration and 1.25 litres per minute compared to water at 0.25 litres per minute, and a 64% increase in pressure drop (ΔP) under the same arrangement. The innovation lies in the synergistic use of TiN nanofluid and twisted-tape inserts to enhance collector efficiency. This work demonstrates the capability of TiN nanofluid and twisted-tape inserts to markedly increase the thermal efficiency of evacuated U-pipe solar collectors, thereby facilitating enhanced solar energy use [15].

Heyhat and Al-Shiblawi (2025) presented hydrophobic twisted tapes as a method to reduce pressurelosswhilemaintainingimprovedheattransmission.Arangeoftwistedtapeswith varying widths and twist ratios were manufactured and experimentally evaluated under laminar and turbulent flow conditions, concentrating on pressure drop, efficiency, and performance index. The findings indicate that hydrophobic twisted tapes may increase the performance index from below 1 to above 1. At a flow rate of 50 Lph, the performance index of the twisted tape with a hydrophobic surface improved by 125%. It was noted that increasing the tape width and decreasing the twist ratio resulted in a higher pressure drop, enhanced efficiency, and an improved performance index. The research also tested the performance of twisted tapes with constant widths against those with variable widths. Experimental results show that twisted tapes with varying widths outperform those with continuous widths. At a flow rate of 50 litres per hour, the performance index of the variable-width twisted tape with a hydrophobic surface improved by 143% [16].

Jambulingam et al. (2024) experimentally tested innovative twisted tape designs in solar water heaters to optimize heat transfer and reduce flow resistance. Key findings show enhanced Nusselt numbers and thermal performance factors via novel twist geometries, balancing swirl intensity against friction penalties. Implications include scalable, passive augmentation for flat-plate/evacuated-tube SWH, with correlations for design. Builds on prior tape studies (e.g., V-cut, helical) [17].

Munusamy et al., (2024) analyzed a parabolic trough SWH using copper dimple-textured tubes with aluminum coating and helically twisted tapes experimentally. Results reveal collector efficiencies of 46-48% (vs. 44-46% plain) across 0.5-2.5 kg/min flows, due to turbulence and reduced friction. Nusselt numbers rose with flow, dimples boosting convection. Uncertainty analysis confirms reliability; recommends for high-heat-flux applications. Reviews helical tapes' swirl benefits [18].

Abd et al. (2025) experimentally studied obstacles in solar heaters to improve outlet temperatures in natural circulation. Insertions disrupted boundary layers, elevating fluid temps by promoting mixing without excessive pressure drops. Key results: significant thermal gains under varying insolation, suitable for thermosiphon systems. Complements insert literature; future scope includes optimized obstacle shapes for exergy efficiency. Limited details on geometries/parameters [19].

Thulasi et al. (2020) evaluated convex lens SWH with serrated, triangular-cut, and perforated twisted inserts. Experiments showed superior heat transfer (higher Nu, efficiency) from cut/perforated designs via intensified turbulence vs. plain lens focusing. Serrated best for low-Re; perforated optimal thermo-hydraulically. IOP conf. paper; contributes cut-twist variants to lens-augmented SWH, citing prior perforations' merits [20].

Radhi et al. (2025) combined experimental/numerical analysis of flat-plate solar collector with square coil and twisted tape inserts. Hybrid augmentation yielded elevated Nu, friction trade-offs manageable; validated CFD against data. Efficiency improved via dual swirl/vortex generation. Case Studies in Thermal Eng.; advances compound passive methods, correlating performance for design. Builds on single-insert baselines [21].

III. EXPERIMENTAL WORK DONE ON SOLAR WATER HEATER

Table No-1

Paper	Methodology	Parameter	Results	Future Scope
Kumar and Prasad (2000)	Experimental research on solar water heaters with twisted tape inserts inside flow tubes; performance measured at various Reynolds numbers and solar radiation levels.	Re=4000-12000 Y(twist ratio)=3-12 M=0.05-0.2 kg/sec	Thermal performance enhanced by about 30% versus flat-plate solar water heaters; better performance at Re ≈ 12,000; improved efficiency at higher solar radiation.	Performance improvement plateaus beyond certain Reynolds number; specific to tested conditions; scaling to other designs not discussed.
Jaisankar et al. (2008)	Experimental study on thermosyphon solar water heaters with Left-Right twisted tape inserts of various twist ratios; measurement of Nusselt number, friction factor, thermal efficiency.	Re=3000-23000 Y(twist ratio)=3,4,5,6	Left-Right twisted tapes improve thermal performance by inducing swirl flows; significant heat transfer enhancement despite friction increase.	Test limited to thermosyphon systems and specific twist ratios; increased friction factor may impact pumping power; results site-specific.
Bhakta et al. (2018)	Experimental evaluation of cylindrical parabolic concentrating solar water heater with nail-type twisted tape inserts of varying pitch ratios.	Twist ratio=4.787,6.914,9.042, L=1.220,Di=0.023,DO=0.025	Smaller nail pitch ratios substantially improved thermal efficiency and energy storage due to enhanced swirl and turbulence.	Specific to tested CPCSWH configuration; cost and durability not addressed; limited environmental conditions tested.
Gracia et al. 2017	Pressure drop loop (1.4 m copper tube, differential sensors); heat transfer loop (insulated collector rig, Pt100 sensors, absorber thermocouples at multiple sections).	Re=80-9000 (friction), Re=400-2500 (heat transfer); inserts: p/d=1.0-24.0, e/d=0.07-0.28; water at Tin=15°C, Pr≈7-8.	Fi/fs=1.3-79.8; best ΔTw=5.90°C (WC01), ΔTa=5.40°C (WC01) at Re≈1500; all inserts reduce absorber temperature, WC01 optimal for serpentine collectors (fi/fs=2.8 at Re=1000).	Suitability for harp-type collectors (pressure drop less critical); WC01 recommended for serpentine due to low friction/early turbulence; further thermo-hydraulic criteria like R3m.
Ramesh et al. 2018	Experimental setup with Al pipes, V-cut tapes inserted; heat absorbed via radiation, conducted to water; compared to plain tube/twisted tape.	Flow rate=144 L/h (0.04 kg/s, turbulence up to Re≈5000); V-cut width/depth=10 mm; water as medium.	Optical efficiency +15%; heat loss -30%; superior Nusselt, heat transfer, friction vs. plain tube in laminar/transitional/low-turbulent flows.	Compact/efficient designs; further validation of numerical models; optimization for real installations, possibly with nanofluids or hybrid inserts.

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Paper	Methodology	Parameter	Results	Future Scope
Karwa and Sharma (2015)	Experimental tests of solar water heaters with full and partial width twisted tape inserts under laminar to moderate Reynolds numbers.	Re=125=500,mf=5-20kg/s,L=1.5m,twist ratio=3,5,width=75%	Thermal efficiency increased by 4.5-8%; partial width tapes create higher velocity annular gap enhancing heat transfer more effectively.	Limited to low and moderate Reynolds numbers; results may not extend to turbulent flows or other configurations.
Amleshaal et al., 2020	Thermosyphon heater with twisted tapes (y=3), rod/spacer (150-450mm) tested outdoors; measured temps, flow, pressure for efficiency via thermocouples, meters.	Rod/spacer lengths: 150/300/450mm; twist ratio y=3; ~20-25mm tubes; laminar natural convection; 30-45° tilt, varying solar intensity.	Rod: 24% heat loss cut, 53% friction drop at 450mm; spacer: 33%/56%; better efficiency than plain tube.	Optimize lengths/positions; test nanofluids/climates; compare tapes; CFD modeling; integrate coatings/PCM for superior thermosyphon performance.
Bora and Bhatt (2020)	Comprehensive review of heat augmentation methods in solar collectors focusing on turbulator inserts; analysis based on temperature application, pressure drops, flow types and fluid properties.	Re=200-8000, Pr=5 to 8,Y=3,	Different turbulator inserts improve thermal efficiency; appropriate turbulator selection depends on application parameters; extensive body of experimental data.	Largely review-based; lacks new experimental data; contextual application may vary.
Chaudhary and Namjoshi (2021)	Experimental comparison of short and long pitch twisted tape inserts inside evacuated tube solar water heaters; measurements under varied flow rates and thermal conditions.	Di=20mm,DO=40mm, L=1m mf (LOW FLOW RATE)=.00136Liter per second mf(Medium flow rate)=.00144 Liter per second.	Short pitch twisted tapes produce more turbulence; better increase in water temperature gain than long pitch tapes; effective, cost-efficient enhancement strategy.	Focused on evacuated tube heaters; limited flow rates and climatic variations studied.
Ananth et al. (2022)	Outdoor experimental evaluation of customized Kenics twist inserts with rods and spacers in domestic solar water heaters; thermal and hydraulic data collected across multiple days under consistent climate.	Re=200- 1800,L=0.125 to.5m Nusselt no. -5-25	Rods and spacers reduce flow resistance and pressure drop compared to full-length twists; moderate decrease in Nusselt number; higher efficiency than plain tubes.	Fixed twist ratios and insert lengths; results limited to local climate; trade-off between heat transfer and flow resistance noted.
Puthilibai et al. (2022)	Experimental testing using aluminum twisted tubes as	Twist ratio- 2.5 Temp inlet- 29 degrees Celsius	Twisted tape inserts accelerated heat	Limited to aluminum twisted tubes; no direct comparison

	inserts to enhance heat transmission in solar water heaters; temperature uniformity and water temperature rise measured.	Outlet temp-71 degrees Celsius Material-aluminum strip.	transmission; maintained uniform temperature in tube; increased average water temperature by up to 11 °C.	with other insert types; specific experimental setup.
Patel (2023)	Design and experimental evaluation of solar water heater with twisted copper tubes; measurement of temperature profiles and thermal performance under typical domestic conditions.	Mass flow rate- 0.002kg/sec Efficiency-21.89%- 32.10%	Twisted copper tubes significantly increase turbulence; improve thermal efficiency and heat gain over standard tubular heaters; validate twisted tubes efficacy.	Focused on domestic conditions; scale-up and cost analysis not included; fouling behaviors not studied.
Shafieian et al. (2023)	Comprehensive literature review of concentrated solar water heaters (SWH); analyzed spinning mirror concentrators' effects on performance metrics across studies.	Concentrated SWH variants vs. conventional flat-plate/evacuated tube types; spinning mirrors for high-temp focus; energy efficiency 63-83%.	Concentrated SWH achieved elevated temperatures superior to conventional systems; spinning mirrors boosted modified SWH efficiency to 63-83%.	Optimize spinning concentrator designs; hybridize with nanofluids/PCM; field trials for scalability; cost-benefit analyses in diverse climates.
Deshmukh et al. (2025)	Experimental study on solar collectors enhanced with titanium nitride (TiN) nano-fluids combined with twisted tape inserts; variable nanoparticle concentrations tested for heat transfer and pressure drop effects.	TiN nanofluid (40–50 nm, 0–0.1 vol%); flow: 0.25–1.25 LPM (laminar); twist ratio H/D=5; irradiance 1000 W/m²; location Sangamner, India (19.5761°N, 74.2070°E); Cu U-pipe Ø10.7 mm.	Substantial heat transfer augmentation with TiN nano-fluids and twisted tapes; pressure drops increased by 64% under similar conditions; improved solar collector efficacy.	Increased pressure drop leading to higher pumping power; long-term stability and cost-effectiveness of nano-fluid not evaluated.

Heyhat and Al-Shiblawi (2025)	Experimental testing of hydrophobic twisted tapes with varying widths and twist ratios under laminar and turbulent flows; assessment of pressure drop, efficiency, and performance index.	Pure water; flow: 50–250 Lph (50/75/100 laminar, 150/200/250 turbulent); tape: width 12/16/20 mm fixed or 20–0 mm var., TR=5/7/9, thick. 1 mm; inlet 30°C; Cu tube Ø28 mm; Tehran summer.	Hydrophobic twisted tapes improved performance index by 125%-143%; variable-width tapes outperformed constant-width; wider tapes and lower twist ratios increased pressure drop and efficiency.	Impact of fouling over time unknown; manufacturing complexity of varying widths; limited flow rates tested.
Jambulingam et al. (2024)	Fabrication and outdoor testing of customized hybrid twist inserts combining helical, left-right, and Kenics designs with rods and spacers in residential solar heaters; comprehensive thermal and hydraulic data.	Twist type: full twist, twist+rod (125/250/500 mm), twist+spacer (125/250/500 mm) (Y=3). - Reynolds number (laminar, thermosyphon). - Nusselt number, friction factor. - Heat removal factor, instantaneous efficiency, overall heat-loss coefficient.	Full-length twists nearly tripled thermal efficiency compared to plain tubes but doubled pressure drop; modified inserts reduced pressure loss while maintaining gain.	Fouling, pumping power increase concerns; limited twist ratio/environmental conditions tested; operational challenges noted.
Munusamy et al. (2024)	Experimental analysis of parabolic-trough solar water heater with helically twisted copper tubes, with and without copper dimple texturing plus aluminium coating; outdoor tests in Coimbatore with varying mass flow rates through receiver (0.5–2.5 kg/min); evaluation of collector efficiency, friction factor, Nusselt number, convective heat-transfer coefficient and uncertainty.	Tube type: plain vs copper dimple tube with Al coating and helically twisted tape. - Mass flow rate: 0.5–2.5 kg/min. - Re based on tube conditions; ΔP, f, Nu, h, collector efficiency; pressure drop (~2.32 kPa).	At 1.5 kg/min, solar collector effectiveness improved by about 31.2% compared to plain tube. - Friction factor increased by ~0.23, convective heat-transfer coefficient enhanced by ~7%, and Nusselt number rose to nearly 298 for dimpled, Al-coated twisted-tube receiver; overall uncertainty ±2.3%.	Study different dimple geometries, coating materials, and twist ratios to further optimise thermo-hydraulic performance. - Compare with alternative receiver designs (corrugated, finned, nanofluid-based). - Extend to low- and moderate-insolation regions and industrial process-heat applications.
Hussain Saad Abd et al., 2025	Experimental investigation of all-glass evacuated-tube SWH (200 L tank, 16 tubes) in Baghdad for ~4 months with natural circulation; comparison of plain tubes and six	Tape length 1.2 m, width 50 mm. - Twist geometries: normal, regularly spaced, triangular, rectangular, semicircular, drilled. - Daily solar radiation (~780–1100 W/m²). - Tank water	Final tank temperatures for plain vs six twisted tapes: 53.6, 56.7, 60.4, 66.4, 71.6, 77.8, 82.4 °C, showing substantial gains with inserts. - Daily energy efficiency increased by 9.7,	Optimise twist geometry and minimal twist ratio to maximise efficiency while limiting flow resistance and cost. - Analyse pressure drop and pumping power explicitly for forced systems. - Extend

	aluminium twisted-tape geometries (normal, regularly spaced, triangular-cut, rectangular-cut, semicircular-cut, drilled) inserted into copper riser pipes; hourly monitoring of solar radiation, ambient and tank temperatures, and calculation of stored energy and efficiency.	temperature rise, hourly and daily energy efficiency.	8.6, 6.3, 5.4, 4.9, and 4.3 percentage points for the six tape types compared with no tape; "type 6" (drilled twisted tape with compact circular geometry) gave the highest improvement.	study to different climates and hybrid systems (e.g., nanofluids, PCM storage).
S. Thulasi et al., 2020	Experimental study on a flat-plate solar collector (1 m × 1 m) fitted with nine parallel copper risers, top glass plate carrying ~45 convex lenses to focus diffuse radiation, and novel combined twisted inserts: CSPT (combined serrated + perforated) and CTPT (combined triangular-cut + perforated), at twist ratios 3 and 6; comparison with plain collector; evaluation of Nu, friction factor and instantaneous efficiency using Hottel–Whillier analysis.	Twist types: CSPT-6, CTPT-6, CSPT-3, CTPT-3. - Twist ratios Y=3 and 6 (riser ID ≈11 mm). - Re ≈190–1266 (laminar). - Nu range 4.1–16.7; friction factor 0.035–0.1155.	Average Nu for plain, CSPT-6, CTPT-6, CSPT-3, CTPT-3: 4.70, 9.46, 10.74, 12.87, 14.13 respectively; CTPT-3 gives highest Nu. - Mean efficiencies: 49.77% (CSPT-6), 53.47% (CTPT-6), 59.8% (CSPT-3), 61.03% (CTPT-3); CTPT-3 achieves ≈1.9× higher efficiency than CSPT collector and ≈9 percentage-point improvement over conventional collector.	Further optimisation of CTPT geometry (hole size, spacing, twist ratio) to enhance heat transfer with controlled friction. - CFD benchmarking and scaling to larger systems. - Explore other concentrating elements and different working fluids / nanofluids
Firas Abdulamir Radhi et al., 2025	Combined CFD (SolidWorks + ANSYS Fluent) and indoor experimental study of three water-cooled PVT serpentine collectors mounted behind a PV module: smooth tube (SCST), smooth tube + twisted tape (SCST-TT), and smooth tube + twisted tape + square spring (SCST-TT-SQS); constant irradiance 400–1000 W/m², mass flow 0.0166–	Designs: SCST, SCST-TT, SCST-TT-SQS. - Mass flow: 0.0166–0.0498 kg/s; inlet water 25 °C. - Heat flux: 1000 W/m² in simulation; indoor irradiance 400–1000 W/m². - Parameters: module temperature, Nu, f, THPF, heat gain, thermal & electrical efficiency, overall efficiency.	Max surface temperatures: 63.56 °C (SCST), 61.78 °C (SCST-TT), 58.8 °C (SCST-TT-SQS); average panel temperature significantly reduced with SCST-TT-SQS. - At 1000 W/m² and 0.0498 kg/s, SCST-TT-SQS achieves thermal efficiency 76.04%, maximum heat gain ≈181.3 W, and overall efficiency 88.73%, higher than SCST and SCST-TT; electrical efficiency also improved	Further optimisation of square-spring and twisted-tape geometry for higher THPF with moderate pressure drop. - Exploration of nanofluids, PCM, and alternative tube materials for PVT. - Techno-economic and lifecycle analyses for large-scale deployment.

	0.0498 kg/s; evaluation of temperature field, Nu, friction factor, thermal-hydraulic performance factor (THPF), and energetic performance (thermal, electrical and overall efficiencies).		due to better cooling.	

IV. ROLE OF COATING ON PIPES IN IMPROVING THE PERFORMANCE OF SWHS

Poongavanam et al. (2023) Experimented SWH through shot-blasting to rough up absorbers, ACNM coating through spray and DIW-ACNM nanofluids as HTF. NFs (zeta/SEM validated) were found to exhibit increasing 7.5-12.04 F. This gave 52.7 effectiveness that compensated 23.5 pressure and 22.1 pumping raise and produced 1.14 performance factor. Synergistic ACNM dual use plus surfacing drives Powers high thermal gains, which favors eco-friendly upgrades [22].

Meena et al. (2022) created and tested a prototype solar-assisted heat pump water heater (SAHPWH) in the natural conditions of the buildings to improve their performance in terms of energy savings. The system was found to have a COP of approximately 6 and heat gains were consistent with single glazing and 600750 W/m^{2}irradiance. A flat-plate collector (1.83 m 1.22 m 0.1 m with 0.5 mm black copper absorber and transparent cover), was used to heat 60 L of water between 15^o C and 45^o C in approximately 70 min at 700 W/m^2 average insolation. The factor of collector efficiency (F) is positively related with the characteristics of the absorbers, but negatively related to the spacing of the tubes, which highlights the existence of great commercialization opportunities to solar-rich regions interested in reducing building energy consumption [23].

Ramesh et al. (2022) used the black-chrome (BC, 0.91, 0.16) and nickel-cobalt (Ni-Co, 0.92, 0.34) coatings on the copper absorber panels in SFPCs which were supplemented with reflectors to concentrate solar flux. After making response surface methodology (RSM) using Box-Behnken design, they examined the data through ANOVA by varying flow rate (1.28-1.32 L/min), collector tilt (43.89 -46.91), and reflector angle (42.34-44.92). BC panels performed improvements over Ni-Co by 10.1% (max η=89.3% vs. 79.2%), since it has lower emittance; mean efficiencies of 58.67 and 50.19, respectively, reflect the advantage of selective coatings in high-efficiency solar thermal systems [24].

Fadzlin et al. (2022) experimented that the residential hot water, commercial DHW, and space SWHs make up a significant portion of global solar thermal power, helping to supply energy and reduce GHGs: 63, 28, and 9 percent, respectively. There are however, global technical and industrial challenges that keep adoption at bay. The paper critiques the problem of domestic SWH, particularly the use of thermal energy storage (TES) to maximize the capture of collector irradiance and the system effectiveness. Similarities between countries highlight the role of unresolved obstacles in the expansion of solar thermal [25].

Nurhilal et al. (2024), experiment involved corrugated absorber plates made of aluminum and zinc-coated steel in the dry and rainy seasons of Indonesia and the no-load performance and performance with water-heating. Increased insolation existed during dry seasons. The averages of no-load efficiencies were 41.45% (aluminum) and 33.94% (zinc-coated steel); water-heating efficiency was reduced to 20.40% and 10.47%, respectively. Aluminum was superior in absorption potential whereas zinc coated steel was cost effective. These two materials were viable all year round and efficient, affordable, and resilient to suit various climates [26].

Alabi et al. (2026) offer a comprehensive review of experimental strategies to enhance the heat performance of solar water heating (SWH) systems, focusing on collector design, absorber enhancements, nanofluids, phase change materials (PCMs) and integrated photovoltaic-thermal (PVT) collectors. The authors demonstrate that flat-plate, evacuated tube, concentrating and integrated collector-storage collectors have different strengths, but are all plagued by heat loss, limited storage capacity, and diminished performance under non-optimal sunlight conditions. It reviews studies that report improvements from turbulators, selective absorber coatings, reflectors, corrugated absorbers, nanofluids, and PCM-integrated tanks, noting that some designs have achieved over 60% improvement in thermal efficiency. The strength of the review is its comparative discussion of experimental results, but it also identifies ongoing challenges with long-term stability, scalability and economic feasibility for practical applications [27].

Azha et al. (2020) discuss approaches to enhance the heat-transfer performance of flat plate solar collector (FPSC) solar water heaters.

The authors list ten significant methods, among them nanofluids, absorber coatings, PCMs, heat-loss reduction, polymer materials, turbulators, mini- and microchannels, and new collector designs. It reveals that the main enhancements are due to increased turbulence, mixing, heat-transfer area and heat capacity. The paper also makes particular mention of vibration-induced heat-transfer enhancement, which can be achieved with low-frequency vibration and evacuated-tube collectors have reported efficiency up to 78%. But the authors note that vibration has not been well investigated for FPSC systems, and it should be further explored [28].

Tsoukpoe et al. (2026) investigate the field performance and user satisfaction with water-in-glass evacuated-tube collectors in Ouagadougou, Burkina Faso. The paper draws on survey data, market studies and literature reviews to demonstrate that WiG-ETCs have emerged as the most popular solar water heating technology because they offer lower costs (relative to flat-plate collectors) and fit with local markets. It also clarify that they tend to have good thermal performance and high user acceptance, but are plagued by common problems such as float-valve malfunction, leaks, corrosion, and tank deterioration. One of the impacts of the paper is to consider factors beyond laboratory performance to the realm of durability and maintenance, noting the need for corrosion-resistant stainless-steel tanks and improved component reliability to ensure sustainability [29].

Saint et al. (2018) examine methods to improve heat retention in integrated collector storage solar water heaters (ICSSWHs), a compact solar thermal system that integrates the collector with the storage tank. The authors explain that ICSSWHs are appealing due to their simplicity, cost-effectiveness, and compactness, but they suffer significant heat losses when not collecting. The paper reviews many strategies to improve heat retention, such as extra insulation, transparent insulation, night covers, baffles, fins, glazing improvements, phase change materials (PCM), reflectors, selective coatings, and inlet design. The review reveals that many such strategies enhance heat retention and stratification, particularly double glazing, baffles, and PCM storage. But the paper finds that although PCM works well, it might be expensive and complicated, while insulation, baffles and glazing are simpler and cheaper for residential systems [30].

V. ADVANCEMENT WORK ON SOLAR WATER HEATER

TABLE NO.-2

Author	Methodology	Parameter	Result	Future Scope
Poongavanam et al. (2023)	Shot-blasting absorber, ACNM spray coating, DIW-ACNM nanofluids as HTF.	ACNM vol% (0-0.4), ΔT, efficiency.	η=52.7% at 0.4 vol%, PAF=1.14 despite ΔP+pump↑.	Scale bio-derived ACNMs for commercial SWHs.
Meena et al. (2022)	Prototype SAHPWH testing with single-glazed FPC under real conditions.	Irradiance (600-750 W/m²), COP, heat gain.	COP~6; 60L 15-45°C in 70min at 700 W/m².	Hybridize with buildings in solar-rich areas.
Ramesh et al. (2022)	RSM-Box-Behnken on BC/Ni-Co coated Cu panels + reflectors.	Flow, tilt, reflector angle; ANOVA analysis.	BC η=89.3% max, outperforms Ni-Co by 10.1%.	Optimize RSM for industrial selective coatings.
Fadzlin et al. (2022)	Review of domestic SWH challenges, TES integration globally.	Capacity shares, technical/industrial hurdles.	63% residential; TES aids performance but barriers persist.	Policy for TES-SWH adoption worldwide.
Nurhilal et al. (2024)	Seasonal testing (dry/rainy) of Al/zinc-coated steel absorbers.	No-load/water-heating efficiency across seasons.	Al:41.45%/20.40%; Zinc:33.94%/10.47% avg η.	Hybrid materials for tropical climates.

Alabi et al. (2026)	Comparative review of recent experimental studies on enhanced solar water heating systems.	Collector type, nanofluids, coatings, PCM, PVT systems, exergy and thermal efficiency.	Reported thermal efficiency gains above 60% in some enhanced designs; identified major practical limits.	Better PCM development, nanofluid stability studies, AI-based optimization, scalability and durability testing.
Azha et al. (2020)	Review of thermal performance enhancement methods for flat plate solar collector solar water heaters, with focus on vibration.	Nanofluids, coatings, heat loss reduction, PCM, turbulators, modified geometry, vibration frequency.	Identified ten enhancement methods; vibration in ETSC achieved up to 78% efficiency, but FPSC vibration research is limited.	Experimental vibration studies on FPSC, reliability under vibration, combination with other enhancement techniques.
Tsoukpoe et al. (2026)	Field survey, market analysis, and literature review of water-in-glass evacuated tube solar water heaters in Burkina Faso.	Operational status, failures, tank material, tilt angle, maintenance history, user satisfaction.	94% systems operational; common failures were float valves and leaks; stainless-steel tanks showed better durability.	Improve float-valve reliability, promote corrosion-resistant tanks, expand field-based long-term performance studies.

VI. ECONOMIC IMPORTANCE OF COLLECTOR DESIGN

Arnaoutakis et al. (2022) discuss a new ICS solar water heater with an asymmetric compound parabolic trough of concentrating (CPC) coupled with a double-walled cylindrical storage tank, and partially depressurized annulus in which a small water layer is placed which promotes heat transfer between outer and inner cylinders. An algorithm to optimize the geometry and system sizing of computers using many criteria can optimize thermal output, fabrication cost and environmental impact, such as the best number of ICS units to use under certain operating conditions. Life Cycle Assessment (LCA) is used to measure the environmental footprint of the device and thermal energy generation is measured with regards to storage conditions, solar irradiance and annulus pressure. The work has shown that multi-criteria design under integrated approach can provide ICS design configurations that are thermally efficient and cost and eco-effective which offer valuable design considerations towards tailoring next generation solar water heaters with reduced lifecycle effects [31].

Yaseen et al. (2024)evaluated a reformulated thermosiphon solar water heater during a period of 12 months in Amman, Jordan, with the ambient/inlet/outlet/storage temperatures and tilted solar irradiance being monitored. The performance depended on the rate of collector flow and incident radiation with the highest efficiencies at midday. No-consumption heat gain, with-consumption, and daily η were highest at 200.55 MJ no-use (September), 304.81 MJ with-use (September), and 54% no-use (May), 55% with-use (September). The design is good in maximum solar hot water use in the mid-latitude locations and it shows strong efficiency on an inter-season basis [32].

Pambudi et al. (2024) experimented that three prototypes of SWH collector (Model A square polycarbonate), Model B V-corrugated zinc and Model C trapezoidal aluminum were tested at the real summer conditions in Indonesia and the researchers observed the radiation, wind speed, temperatures, and flow rates after every 10 minutes with trickle/one-way systems. Model B provided maximum overall efficiency (50%), moving above Model A(47) and Model C (34). A flow rate of 120 L/h was better than 240 L/h and better in configurations. Any of the models can be applied in domestic settings: polycarbonate is the most cost-effective and can be deformed or have a short life, whereas zinc/aluminum versions are durable. V-corrugated zinc is found to be optimal in tropical climate to balance between efficiency, life, and cost-effectiveness to enable scalable SWH deployment [33].

Patel (2023) studied that was based on a mixed-methodology to integrate literature review on qualitative research and SolidWorks CAD modeling to enhance the efficiency of SWH using new designs. Important considerations such as materials, geometry and integrations come into play as the determinants of high energy capture and transfer. CAD prototype is an illustration of the improvements to be made, highlighting the interdisciplinary cooperation, policy facilitation, and user training to be adopted. The further work given the priority should focus on field prototyping, simulations and sustainable scaling to mainstream innovative SWHs [34].

Eze et al. (2024) found that solar water heaters provide more environmentally friendly thermal energy harvesting of sunlight to domestic applications such as space heating, showers, cooking and hybrid standard applications in chemicals, power and construction. Although there are improvements, technical/economic barriers are constraints to a large scale adoption compared to fossil/electric alternatives. In this paper, the research gaps and the future directions of the paper are identified, select recent literature on SWH thermal efficiency influences (parameters, components) and techno-economic viability are considered. It is unique in its combination of technical and economic analysis and offers researchers a succinct overview of SWH status, encouraging more innovation but not purporting to be exhaustive [35].

Demir et al. (2024) propose a new bio-waste-fired multigeneration system with solar thermal field and atmospheric water collector. The approach integrates thermodynamic, exergoeconomic and environmental analyses with MATLAB and Aspen-HYSYS software, and simulates sewage sludge digestion, gasification, Rankine, Brayton, and organic Rankine cycles. The system considers sewage sludge characteristics, biomass flow rate, air inlet temperature, relative humidity, energy and exergy efficiencies, carbon emissions, and product cost. The process aims to generate electricity, hydrogen, heat and freshwater. Results show outputs of 17,920 kW electricity, 3,207.6 kg/h hydrogen, and 5.14×10^3 L/s freshwater, with energy and exergy efficiencies of 35.76% and 40.49%. Research findings reveal gasification and digestion are major exergy destroyers, and solar and biomass integration enhances environmental sustainability. The potential for improvement includes cost reduction, better gasification, and better waste-heat recovery and solar integration for higher sustainability [36].

Garnier et al. (2018) summarise integrated collector-storage solar water heaters (ICS-SWHs), their application for cold climates, and particularly for building integrated systems. The research approach is a literature review, numerical and experimental modelling of a new rectangular ICS-SWH for Scottish buildings. The parameters include the bulk water temperature and absorber plate temperature, stratification, heat loss coefficient, draw-off rate, auxiliary heating, and the thermal storage efficiency. The findings indicate that the new design enhances thermal storage, achieves a bulk water temperature 6.3 °C higher than the previous design, and increases stratification, but makes heat retention during cooling more complicated due to the increased aspect ratio. The authors conclude that the next steps in research should be to improve building integration, auxiliary heating control and thermal losses at inlet/outlet connections, and realistic modeling of the discharge phase, to enhance end-user performance and seasonal reliability [37].

Vardan et al. (2025) discusses the latest developments in solar water heating systems, including the technology, materials, optimization of design, controls, heat exchangers, and sustainability. It relies on a categorical review approach using 288 peer-reviewed articles (published between 2014 and 2025) and gathered through a systematic search in Scopus and Google Scholar. The most important parameters are thermal efficiency, solar fraction, capacity utilization factor, net energy ratio, carbon reduction efficiency, payback period and the heat loss coefficient. The review finds that thermosyphon systems are typically 3050% efficient, active systems 5070% efficient, and evacuated tube collectors can be up to 75% efficient. To enhance the reliability, sustainability, and real-world implementation, future research must focus on field validation of advanced materials, standardized testing methods, integration with smart grids, and AI-based adaptive control [38].

Saint et al. (2021) survey integrated collector-storage solar water heaters and indicate that their major problem lies in large night-time heat loss, particularly in cold climates such as Scotland. They synthesize earlier work about design features such as insulation, auxiliary heating, baffle plates, fins, glazing, inlet configuration, phase change materials, and reflectors, and show that they are influenced by design features such as insulation, auxiliary heating, baffle plates, fins, glazing, inlet configuration, phase change materials and reflectors. The review also links the thermal performance and whole-life sustainability, and argues that material choice, the possibility of reuse, and design to be reused are essential to reducing embodied impact. Further work is necessary to improve building integration, enhance methods of heat-retention, realistic testing of draw-off, and life-cycle assessment of new configuration under realistic climatic conditions [39].

Hove (2018) created a thermo-economic model to assist in selection of the most cost-effective solar collector, and in setting optimal sizing of a solar water heating system.

The energy-per-dollar metric is used in the study, which is defined as annual collector heat output at the sweet-spot size per annualized life-cycle cost, and maximizes Net Present Value of Solar Savings to determine the optimal collector area. Ten SRCC rated collectors; flat plate and evacuated tube types, were compared under central Zimbabwe conditions, using parameters like collector efficiency, incident-angle modifier, storage tank volume, solar fraction, annual cost. Findings indicate that flat-plate collectors scored the highest overall, with the highest model in the overall ranking of 26.1 kWh/ per m3 of daily hot water demand, an optimal size of 18 m2 per m3 of daily hot water demand, and a solar fraction of 91%. The study concludes that this approach can be applied to other solar water heating systems and locations [40].

VII. ADVANCEMENT WORK ON SOLAR WATER HEATER

TABLE NO.-3

Author	Methodology	Parameter	Result	Future Scope
Arnaoutakis et al. (2022)	Multi-criteria optimization, LCA on asymmetric CPC-ICS design.	CPC geometry, annulus pressure, irradiance, storage conditions.	Optimized ICS with balanced thermal, cost, eco-performance via integrated design.	Next-gen SWH guidelines minimizing lifecycle impacts.
Yaseen et al. (2024)	Year-round experimental testing of natural circulation SWH.	Flow rate, tilted irradiance, temperatures (ambient/inlet/outlet/storage).	Max heat gain 304.81 MJ; η=55% (Sep); robust mid-latitude performance.	Optimal solar utilization in similar latitudes.
Pambudi et al. (2024)	Real-time summer testing of 3 prototypes (poly/zinc/Al) with trickle flow.	Radiation, wind, temp, flow (120/240 L/h) every 10 min.	V-zinc η=50% best; 120 L/h optimal; all viable domestically.	Scalable deployment in tropical climates.
Patel (2023)	Mixed-methods: lit review + SolidWorks CAD modeling.	Design factors, materials, geometry integrations.	CAD prototype shows efficiency gains via novel configs.	Field prototyping, simulations, policy-driven scaling.
Eze et al. (2024)	Literature review on technical/techno-economic SWH aspects.	Efficiency parameters/components, economic viability.	Identifies gaps; framework for technical-economic integration.	Further research addressing gaps for commercialization.
Demir et al. (2024)	Thermodynamic, exergoeconomic, and environmental simulation using MATLAB and Aspen-HYSYS.	Sewage sludge composition, biomass flow rate, inlet air temperature, humidity, energy/exergy efficiency, CO2 emissions.	Produced 17,920 kW electricity, 3,207.6 kg/h hydrogen, and 5.14 × 10^3 L/s freshwater; energy/exergy efficiencies were 35.76% and 40.49%.	Lower capital cost, improved gasifier efficiency, optimized waste-heat recovery, better solar integration.
Garnier et al. (2018)	Literature review plus numerical and experimental study of a new	Bulk water temperature, absorber temperature, stratification, U-value, draw-off rate, auxiliary heat input.	New design improved stratification and storage; bulk water	Better building integration, reduced inlet/outlet heat

	rectangular ICS-SWH.		temperature was 6.3 °C higher than the earlier prototype.	losses, improved auxiliary heating control, more realistic discharging models.
Vardan Singh et al. (2025)	Categorical literature review of recent solar water heating advancements using database search and thematic classification.	Thermal efficiency, solar fraction, capacity utilization factor, net energy ratio, carbon reduction efficiency, payback period, heat loss coefficient.	Active systems and evacuated tube collectors showed high performance; nanofluids, phase change materials, and selective coatings improved efficiency and storage.	Future research should focus on hybrid systems, smart-grid integration, AI-based control, and field validation of advanced materials.
Ruth M. Saint (2021)	Literature review combined with field experiments and life-cycle assessment.	Heat retention, bulk water temperature, stratification, insulation, night cover, embodied energy, carbon payback, hot-water demand.	The baffled system performed better than the finned one; the night cover improved heat retention most, and the system showed economic and environmental viability.	Better building integration, improved heat-retention methods, realistic draw-off testing, and broader life-cycle sustainability studies.
Tawanda Hove (2018)	Thermo-economic modeling using energy analysis and Net Present Value of Solar Savings to compare collectors and optimize sizing.	Collector area, storage tank volume, solar fraction, annual energy output, annualized cost, incident-angle modifier, collector efficiency, hot-water demand.	Flat-plate collectors ranked highest; best collector achieved 26.1 kWh/$, with an optimal size of 18 m2 per m3 of daily hot-water demand and solar fraction of 91%.	Can be applied to other solar water heating systems and locations with different operating temperatures and climates.

VIII. CONCLUSION

The integration of twist-tape inserts into the design of solar water heaters is a simple yet highly effective method for enhancing thermal performance. This review clearly demonstrates that using various twist-tape configurations can substantially increase performance. The efficiency gains suggest that these passive enhancement techniques are suitable for practical implementation in solar thermal systems. Future work should focus on optimizing twist-tape design parameters for specific climatic conditions and operational settings, and on evaluating long-term performance and economic feasibility.

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