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SOLAR PHOTOTHERMIC CONVERSION BY WASTED TIRE CRUMBS FOR WATER HEATING UNDER THE CIRCULAR ECONOMY PERSPECTIVE

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Abstract

Wasted tires are one of the most harmful wastes and are a challenging environmental problem. This project utilized wasted tire crumbs as thermal energy storage and solar photothermic conversion medium for solar water heating. The functionality of the compacted system has been proven experimentally. A solar collector model is developed comprising an open water flow in a U-shape copper piping immersed in a 0.15-m-wide x 0.08-m-high x 1.0-m-long compartment filled with tire crumbs and covered by a Perspex sheet to permit the penetration of the solar radiation. Three water flow rates of 10, 20, and 30 L/h have been used to investigate the system performance. Measurement results show that the tire crumbs could convert solar energy to thermal energy and transfer it to the water inside the pipe. The system performance shows a mean efficiency of 30.5%, 57.5%, and 73% for the 10, 20, and 30 L/h water flow rate cases. The results show that the waste tires are rich in energy materials for solar photothermic energy conversion and thermal energy storage. It is recommended to extend the study by mixing the crumbs with another sensible or latent thermal energy storage material and evaluate the performance in close loop water flow rate.

Keywords: Circular economy, Compact solar water heater, Energy conversion, Tire crumbs, Tire recycling, Waste to wealth.

1. Introduction

The current research deals with using tire crumbs for solar energy storage. Hence, the introduction is split into two main headings to cover the related literature on tire crumbs utilization and the previous research on solar thermal energy storage.

Tires are mainly made of natural or synthetic rubber, which undergoes mixing with acids and solidifying. Rubber is compounded with carbon black (which is a fine soft powder), fabrics, and fillers. It is produced as sheets. Forming the tires from the rubber sheets requires reinforcement by steel wires. However, when reaching end-of-life tires (ELT), they are disposed of in landfills. Approximately 1.5 billion tires are disposed of annually after getting ELT, creating a challenging environmental problem as the tires do not rot down naturally because they are not biodegradable [1, 2]. Wasted tires are one of the most harmful environmental pollutants, which is a real and challenging problem as they can last many decades without degradation.

Ruwona et al. [3] reviewed energy recovery from ELT. They reported that more than three billion new tires were manufactured by 2019, as Freedonia Group World Tires estimated, and only 100 million tires have been recycled annually. In 2016, around 30% of the rubber recovered from ELTs was used in sports fields, and 25% was used on playground surfaces [4]. Worldwide, the main routes for ELT tire recovery are 52% for producing material, mainly rubber and steel wires, and 19% for tire-derived fuel [4, 5].

In many countries, including China and the United States, most scrap tires are handled domestically and dumped in landfills, recycled, or used as fuel in factories producing products like cement and paper [6]. For many developed countries, shipping ELTs for recycling abroad is cheaper than recycling domestically. That helped drive international trade in rubber production from ELTs to about 2 million tons in 2018, from 1.1 million tons in 2013 [6]. Europe United has banned the shipping of tires to landfill sites. Hence, much research and development has gone into the tire recycling direction. Williams [7] has introduced several methods to use products from ELTs. Specialized businesses have been developed to handle ELTs and recycle them as a resource. It is expected to accelerate the development of the tire recycling industry soon [4].

1.1. Tires and tire crumbs recycling and utilization.

Below is some reported use of the ELT tire and materials derived from recycled tires.

I. **Agricultural applications**: Farmers used waste tires in agricultural applications as barriers to control erosion and soli stabilization [8].

II. **Construction industry**: Road and building construction companies have used shredded ELTs as road fillers, as pads for railways, and many other construction purposes [2]. Shredded ELTs have been used as long-lasting protective covers, where it is proven to be non-leachable. Coloured rubber mulches derived from recycled ELTs are widely used in gardens, parks, playgrounds, and equestrian arenas, as reviewed, and discussed by Muzenda [9]. Rubber mulches are said to be permanent and aesthetically pleasing landscape materials.

III. **Wastewater filters**: Shredded ELTs with a specific and standardized size could be used as filters in wastewater treatment plants and constructed wetlands.

Shredded ELTs are better than organic compounds and rocks as they can be chipped to produce highly porous mediums.

IV. Structural Engineering and Construction: Recycling wasted tires is mainly targeted at extracting the rubber compound. Rubber recovered from waste tires is used in various applications. It is used in pure or added material to construct playground surfaces, parking lots, bank stabilization, paved surface filling, and asphalt regulation [10, 11]. Using rubber derived from ELTs and mixed with asphalt for pavements also creates opportunities for tire recyclers. Rubber recovered from tires also improves the asphalt properties by increasing longevity, decreasing cracking, thinner lift, and increasing skid resistance [12, 13]. Asphalt improved from rubber recovered from tires is used for waterproofing membranes, cracking sealing, joint sealing, and roofing materials [14]. Ground-up rubber is now used frequently in asphalt, with many benefits reported by Jin et al. [15]. Roads with rubber have a stronger grip and are 50 percent quieter. They last three times longer than regular tarmac and do not need much maintenance. ELTs-derived rubber is also employed in building applications for retaining walls, erosion control, barricading of shoring embankments, road embankment fills, and thermal insulation [15]. Playgrounds and running track surfaces are commonly rubberized using ELTs-derived rubber [16].

V. The railway industries also deployed ELT-derived rubber [2, 17]. It could be fitted as pads under the rail and tramway tracks to reduce noise and vibration [18]. Switzerland has been adopting this practice since the 1970s. An Italian railway company has built a sleeper made from ELTs, lowering the need for concrete and ballast, and they operate quieter. Thirty-five tons of used tires are used for every kilometre of the track using Green Rail sleepers.

1.2. Energy application

The utilization of tires in the energy field is limited. It has been mostly used as fuel in some industries. To the best of the authors' knowledge, the following are the reported use of ELTs in the energy sector.

I. Fuel: ELTs have been used as fuel in some industries. Tires contain similar energy per unit mass to oil and are higher than gas. Scrap tires have a calorific value of around 33 MJ/kg. Hence, they could be used as an effective fuel for thermal power plants. However, limited negative environmental impacts should be counted, compared to coal. It has been reported that ELTs have been used as fuel in direct combustion in various metal works, paper mills, and tire manufacturing factories. The ELTs have also been used as fuel on a smaller scale in farms, greenhouses, and sewage treatment plants [19,20]. Eddie and Laboy-Nieves [11] investigated the possible use of ELTs for power generation in Puerto Rico. The study estimated that ELTs processed with pyrolysis could supply 379 MWh annually. Old tires can be used as an alternative fuel in production. Entire tires are used in the upper end of a cement kiln preheater. High gas temperatures, 1000 - 1200 °C, cause immediate, complete, and smokeless scrap tire combustion. Alternatively, the ELTs could be shredded into 5-10 mm chips and injected into the pre-combustion chamber of the kiln [19].

II. Thermal Energy Storage: ELT crumbs were utilized in the energy storage application. Al-Kayiem et al. [21] mixed 40%vol tire crumbs with 60%vol concrete, 60%vol paraffin wax, and 60%vol pebbles and tested the mixtures as solar thermal energy storage materials. Sensible thermal energy storage (TES) materials, pebbles, and concrete, with added 40%vol tire crumbs, improved the energy storage capacity. In contrast, latent phase change material (PCM) material, paraffin wax, reduced storage capacity by adding 40% vol. tire crumbs. The added tire crumbs reduced paraffin wax's storage capacity by 43% and increased black-painted pebbles and concrete storage capacities by 54% and 25%, respectively. They recommended investigating solar water heating performance by direct solar absorptivity utilizing tire crumbs.

The recommendations of Al-Kayiem et al. 21] motivated the current research to evaluate the possibility of using shredded tires for energy applications. The end-life tire waste has not been reported previously for the application of solar heating. Hence, the present work aims to develop, investigate, and evaluate a solar thermal system for water heating utilizing crumbs derived from ELTs. The scope of the current work is based on two experimental methodologies. First are property measurements of the tire crumbs, and second are outdoor measurements to evaluate the compact solar water heater (SWH) using tire crumbs as a solar photothermic conversion medium.

The paper is subdivided into several sections. Firstly, related literature on the utilization of ELTs is presented and discussed. The second section describes the methodology and scope of the work with a detailed description of the experimental methods and instruments. The clustered and manipulated measurement results are presented and discussed in the third section, and finally, the findings are concluded in the fourth section.

2. Materials and Methods

This section discusses the experimental procedures used to characterize the tire crumbs and the evaluation of the compact (SWH). The current work is entirely experimental-based research. The experiments are performed in the solar research site at Universiti Teknologi PETRONAS located at 4.3836° N, 100.9712° E.

The tire crumbs used in the current work are purchased from a recycling factory in Malaysia. The crumbs are rubber recovered from shredded ELTs after extracting the stainless-steel wires. They are black in cooler and sticky, as shown in Fig. 1. The Lab measured the tire crumbs' properties, including the size of the crumbs, density, and specific heat.

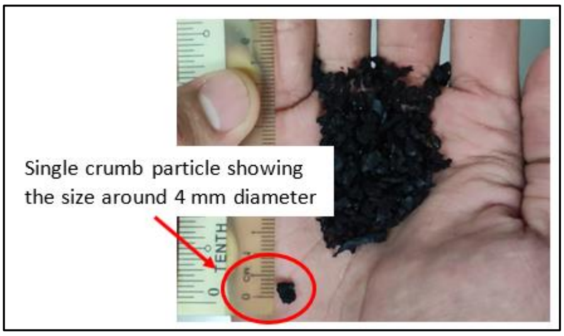

Fig. 1. The rubber crumb extracted from ELTs used in the current compact solar water heater.

2.1. Characterization of the tire crumbs

Density is measured using the simplified procedure of digital balance for weight and the increased volume of water in the baker. The calculated density is 669 kg/m3. According to Gerges et al. [22], crumb rubber or shredded tires have a unit weight or density range between 640 kg/m3 and 720 kg/m3, which justifies the measured density of the ELTs crumb used in the present research. However, further references mentioned other measured density values that are different. It is highly recommended that the user measures the used shredded tires, or the crumbs or powder extracted from ELTs.

The Bomb Calorimeter measures the specific heat capacity as 1230 J/kg·K. Unfortunately, insufficient data on the specific heat capacity of shredded tires and tire crumbs are available. Most literature uses the rubber-specific heat capacity and steel wires to estimate the tires' specific heat. In his technical characterization report of shredded tires, Edeskär [23] used 1600 J/kg·K as the specific heat capacity for rubber, as measured by BLIC [24]. The mean particle volume is 30 mm^3, and the mean weight is 0.021 g.

The procedure for the particle size measurements is discussed in [21], and the same type of crumbs are used. The mean crumb particle diameter ranges from 3 to 5 mm. A crumb particle is illustrated closer to the ruler in Fig. 1 to highlight the crumbs’ size.

2.2. Experimental setup

The experimental setup comprises a compartment made of wood to occupy the crumbs and the water heating pipe. The compartment is made of wood, 1000 mm long x 150 mm wide and 80 mm high. A Perspex sheet covers it to permit penetration of solar radiation. A 6.4 (¼") diameter copper tube with a U-shape is immersed inside the compartment filled with crumbs. The arrangement is shown schematically in Fig. 2.

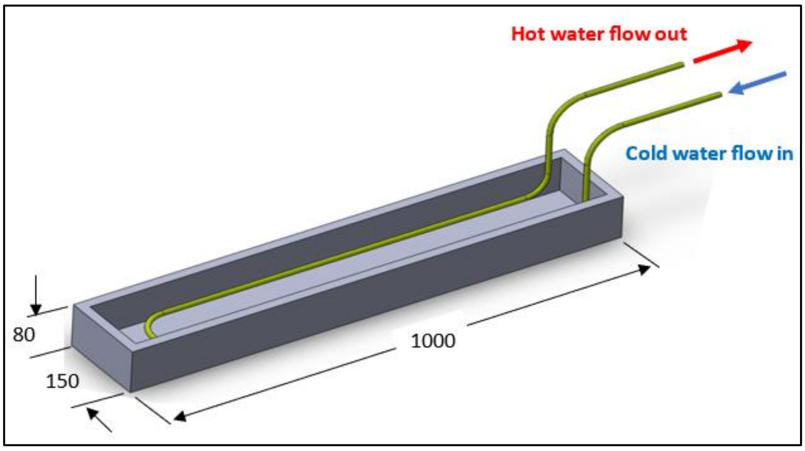

Fig. 2. Schematic of the compact solar water heater using ELT crumbs. (All dimensions in mm).

The setup comprises the compact SWH, open water flow loop, and measuring instrumentation. Water is supplied from the tap to an elevated tank. The water level is maintained by a float that controls the network tap's water supply. The water level in the tank is around 0.7 m higher than the inlet to secure sufficient head to overcome the pressure losses in the water passage. The total length of the U-shaped copper tube immersed in the crumb is 1.8 m.

2.3. Measurements and measuring instruments.

Type-J thermocouple wires were used for the temperature measurements with an accuracy of ±0.75% of the reading. The thermocouple wires were connected to the brand GRAPHTEC GL840 data logger, which has an accuracy of ±1.55 °C within the temperature range of 0 to 500 °C. The incident solar radiation was measured by a Pyranometer-type MS402, which can measure direct and diffuse combined solar radiation. The pyranometer has an accuracy of ±0.2% nonlinearity and 0.2% tilt response within a solar radiation range of 0 to 4000 W/m^2. Some of the instruments used are shown in Fig. 3.

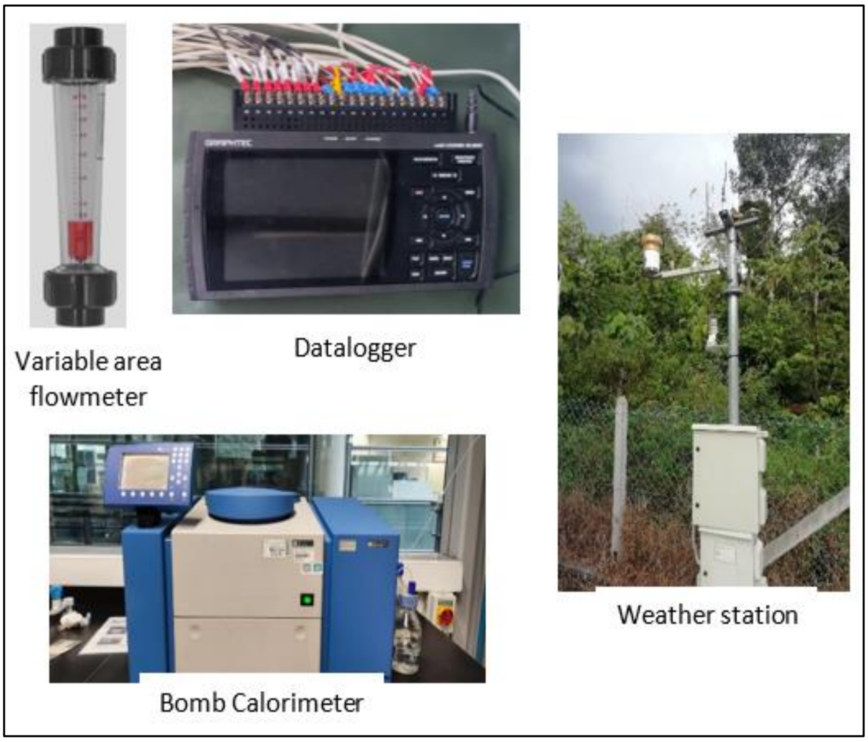

Fig. 3. Photos of the used instruments in the experimental measurements.

Uncertainty in the experimental measurement is essential to quantify the expected accuracy. Table 1 shows the instruments' specifications, including the estimated uncertainty of each variable in the experiment based on the maximum recorded values. Estimation of the material volume in the compartment has ±3 mm accuracy. The ±3 mm accuracy of the volume is due to the 1.0 mm resolution of the measuring tape and the 2 mm propagation of the crumbs' upper surface due to the surface's irregularity.

The maximum systematic uncertainty in the temperature measurement is ±0.8% due to the thermocouple wire and data logger uncertainties. The maximum uncertainty in the temperature measurement is 2.04% due to ±1.6% random and ±0.8% systematic errors. The resulting maximum uncertainty in the predicted heat gain is ±5.78%, which is acceptable and justifies the accuracy of the results.

Table 1. The instruments and estimated uncertainties of measurement variables due to systematic errors.

Variable	Instrument and brand	Accuracy	Max. measured Value	Max. Uncertainty	% of Relative Uncertainty
Solar Irradiance	Type MS402 Pyranometer	±0.4%	880 W/m^2	±3.52 W/m^2	±0.4%
Temperature	Type-J Thermocouples	±0.75%	112.5 °C	.84 °C	±0.75%
	GRAPHTECH GL840 Datalogger	±1.55 °C	112.5 °C	.35 °C	±0.3%
Volume	Measuring tape	0.001 m	0.15×0.08 ×1.0 m	.2 × 10^{-11} m^3	±0.1%
Mass	Digital balance	0.001 kg	25.2 kg	0.0252 kg	±0.1%
flow rate	Variable area LZS-15/Floater Flow Meter	4.0%	30 L/h	0.12 L/h	±4.0%

2.4. Evaluation procedure of the SWH

The evaluation of the developed SWH is based on comparing the system's capability to heat water at three flow rates of 10, 20, and 30 L/h in an open flow loop. First, the measured temperature increase of flowing water over 48 measurement hours is presented in separate figures for each water flow rate. Then, the mean change of water temperature of two days measurement is presented for the three flow rates in one figure to allow comparison between the cases. However, the measured water temperature change is insufficient to clearly indicate the system's performance, as the system's efficiency is the appropriate indicator.

The common procedure of predicting the efficiency of SWH, heat gain to solar input ratio, is not applicable for integrated SWH with TES. Saw et al. [25] proposed a new efficiency prediction for compacted SWH integrated with PCM TES. The procedure is adopted here as the current system is like the one investigated by Saw et al. [25], but a tire crumb is used instead of the Paraffin wax. The procedure counts for the charging and discharging of the thermal energy of the TES as follows:

$$\eta_{thermal} = \frac{Q_{gain.water}}{Solar\ input + Q_{TES}} \tag{1}$$

$$\eta_{thermal} = \frac{\dot{m} \times C_{p.w} \times (T_{w.o} - T_{w.in})}{I \times A + m_{crumbs} \times C_{p.crumbs} \times \left(\frac{T_i - T_{i+1}}{1800}\right)} \tag{2}$$

The thermal storage capacity of the tire crumbs, Q_{TES} (Watt) is the storage charged/discharged thermal power of the tire crumbs, predicted as:

$$Q_{TES} = m_{TES} \times Cp \times \frac{(T_{i+1} - T_i)}{1800} \quad (3)$$

$(T_{i+1} - T_i)$ is the difference between the two current and previous temperature readings within a 30-minute period.

During the charging mode, the new temperature of the crumbs at time i+1 is larger than the old temperature at time i. During the discharge mode, the new temperature, T_{i+1} is less than the old temperature, Ti. Meaning that the Q_{TES} is added to the input energy.

The experimental measurements have been clustered to produce performance indicators and evaluation parameters of the introduced compact SWH in this research. The measurements were carried out at three water flow rates: 10, 20, and 30 L/h. Each flow rate is subjected to two consecutive days of measurements for 24 hours per day.

3. Results and Discussions

This section presents and discusses the results of the experimental measurements. The experiments consist of two parts. The first part is on the characterization of the tire crumbs' properties, which is discussed in the methodology of section 2. The second section is on outdoor experimentation to evaluate the performance of the compact SWH, which is explained in the following sections.

3.1. The experimental environment

The experiment environment data is measured and stored by the weather station in the solar site, including the solar irradiance, the ambient temperature, and the humidity. The solar, ambient temperature and humidity are presented in Tables 2a, 2b, and 2c over two days of each flow rate.

Table 2(a). The average of the recorded weather data during the daytime and night-time for all experimental days.

Experiment With L/h	Solar irradiance (W/m^2)			
	Day 1 17/09/2022		Day 2 18/09/2022	
	Mean	Peak	Mean	Peak
10	499	883	412	627
20	546	878	441	848
30	477	997	401	923

Table 2(b). The average of the recorded weather data during the daytime and night-time for all experimental days.

Experiment With L/h	Ambient Temperature (°C)			
	Day 1 19/09/2022		Day 2 20/09/2022	
	Mean, day	**Mean, night**	**Mean, day**	**Mean night**
10	33.5	28.4	30.1	27.5
20	34	26.8	31.6	27.4
30	32.0	25.7	30.3	25.7

Table 2(c). The average of the recorded weather data during the daytime and night-time for all experimental days.

Experiment With L/h	Humidity (%RH)			
	Day 1 21/09/2022		Day 2 22/09/2022	
	Mean, day	Mean night	Mean, day	Mean night
10	70.1	89	82.5	92.0
20	70.5	90	76.5	91.0
30	72.8	90	79.5	92.4

3.2. Water heating

When the system operates at a 10 L/h water flow rate, the supplied water heats up at a few degrees. The increase in water temperature is recorded as the difference between outlet and inlet temperatures. Water temperature rises after the tire crumbs receive solar radiation and heat up. Not all the received solar energy is transferred as thermal energy to the flowing water, where some solar energy is stored in the crumbs. However, the response to water temperature rise is not instantaneous with solar irradiance, but the heating process of water occurs after 5 to 10 minutes, as shown in Fig. 4.

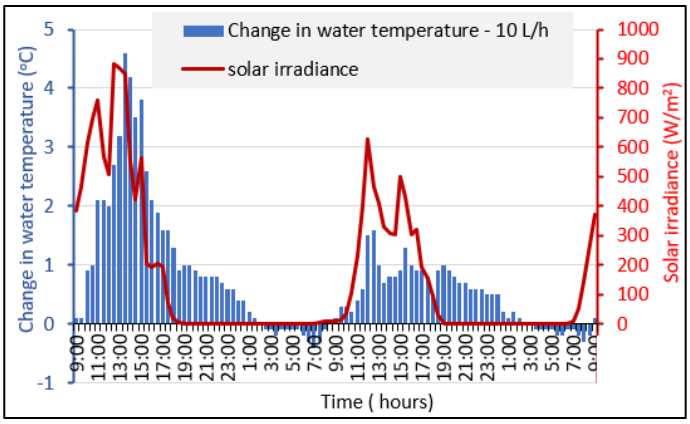

Fig. 4. Transient water temperature change and solar irradiance over forty-eight continuous measurement hours, with a 10 L/h water flow rate.

When the water flow rate increased to 20 L/h, the thermal behaviour of the SWH is shown in Fig. 5 for forty-eight continuous operations. The measured temperatures indicate a similar trend in solar thermal absorptivity and heat transfer from the tire crumbs to the flowing water. Heat is stored in the tire crumbs and discharged to the flow loop after sunset. The other observation noted in the results is that after midnight, the crumbs' temperature is lower than the flowing water temperature, and heat is transferred from the water to the crumbs. Quantifying the amount of thermal energy transfer from solar radiation to crumbs and from crumbs to water is predicted and presented in the coming discussion of results.

There is an analogy between the water flow rate and temperature rise. By increasing the water flow rate to 30 L/h, the system behaviour is presented in Fig. 6. The results of the temperature rise of water flow are less than the cases of 10 and 20 L/h, despite the high solar irradiation, which is almost 1000 W/m^2.

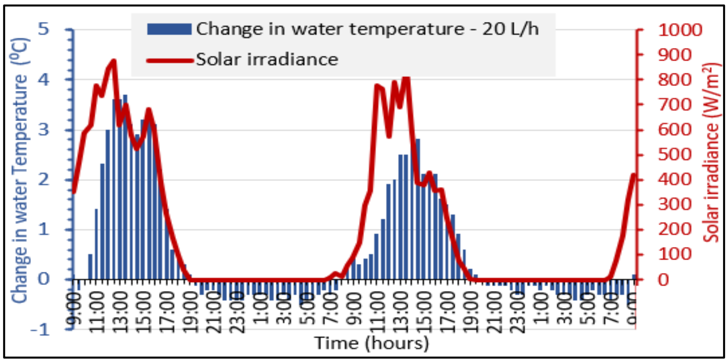

Fig. 5. Transient water temperature change and solar irradiance over forty-eight continuous measurements, with 20 L/h water flow rate.

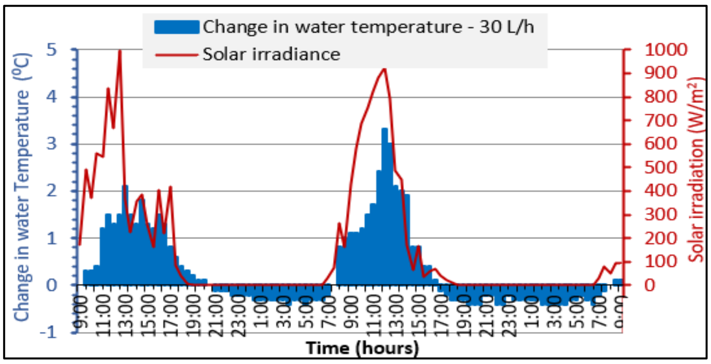

Fig. 6. Transient water temperature change and solar irradiance over forty-eight continuous measurements, with a 30 L/h water flow rate.

Figure 7 compiles the results of water temperature changes for 10, 20, and 30 L/h water flowrate as a mean of two days for each flowrate. For all flowrates, the water temperature increases sharply in the morning and reaches maximum water temperature rise in the mid of the day.

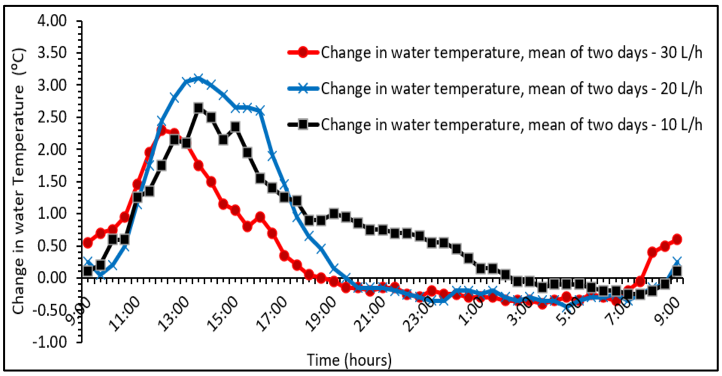

Fig. 7. Comparison between three flow rates in terms of change in water temperature.

The amount of water temperature increase is reduced after 01:00 PM. The case of a lower water flow rate, 10 L/h, has a different trend than the 20 and 30 L/h water flowrate as the water temperature keeps increasing until midnight. In the cases of 20 and 30 L/h water flowrate, the water gained heat until around 07:00 and started to charge heat to the crumbs after 07:00 pm over all night. After sunrise, the flowing water starts to gain heat from solar input, and the crumbs' temperature increases as they gain heat from the solar radiation and store it as thermal energy.

4. Discussion and Analysis

4.1. Analysis of the water heating Performance

The system performance is presented as instantaneous thermal efficiency during solar time for the three tested water flow rates, Fig. 8. The higher water flow rate performs better and efficiently converts solar radiation to thermal energy, heating the flowing water. The efficiency is predicted using the criteria suggested by the compacted solar water heater and TES. The criteria count for the heat of the crumbs during the charging and discharging.

The system's thermal efficiency increases in the morning as the solar irradiance increases and reaches the best performance between 02:00 to 03:00 PM. However, not all the flow rates have the same efficiencies, whereas all have similar trends versus the solar irradiance, increasing in the morning, reaching maximum afternoon, and reducing after 03:00 PM. A comparison of efficiencies is presented in Table 3, showing the maximum and mean efficiencies of the flow rates.

Table 3. The predicted maximum and mean thermal efficiencies of the compacted SWH with tire crumbs TES.

Flow rate (L/h)	Maximum efficiency (%)	Mean efficiency (%)
10	48.3	30.2
20	86	51.6
30	89	69.1

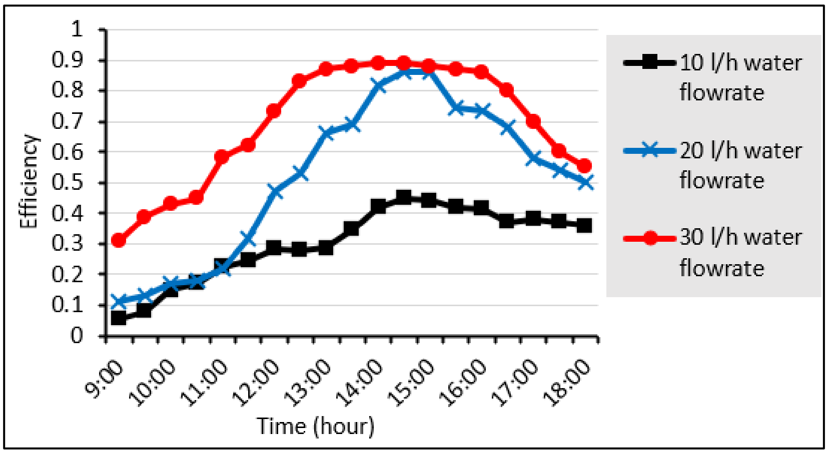

Fig. 8: Thermal efficiency comparison between three flow rates in terms of efficiency during the solar hours.

The interesting finding is that the tire crumbs store solar energy as thermal energy and keep heating the water in the flow loop after sunset. This finding means that tire crumbs perform as solar energy absorbers and thermal energy storage.

However, for all tested flow rates, the efficiency in the afternoon is higher than the efficiency in the morning, even with the same solar irradiance. The reason is that the tire crumbs discharge the stored thermal energy in the afternoon. The crumb's measured temperature is higher than the mean water flow rate in the pipe, and heat transfers from the tire crumbs to the water flowing inside the pipe. This is a great advantage to prolonging the water heating after sunset utilizing the stored energy. To make it clearer, the thermal efficiencies of selected cases in the morning and in the afternoon with the same solar irradiation are presented in Table 4.

Table 4. The predicted thermal efficiencies in the morning and afternoon at similar solar irradiation.

Solar irradiation (W/m^2)	Time in the day	Overall thermal efficiency (%) at		
		10 L/h	20 L/h	30 L/h
325-335	Morning	16.6	24.5	38.0
	afternoon	48.0	68.4	87
545-555	Morning	20	25	40
	afternoon	34	78	89

4.2. Analysis of energy storage capacity

It has been realized from the previous analysis of results that the ELT-derived crumbs can convert solar radiation to thermal energy and function as sensible TES. The received solar energy is divided and received by two recipients: the flowing water and the tire crumbs. In addition to the useful heat gained by water and TES, there are thermal losses to the ambience. However, the crumbs start to discharge heat to the flowing water after the solar input is reduced to less than the stored thermal energy. Figure 9 shows trends of the absorbed energy by water and the thermal charging and discharging of the tire crumbs TES. The amount of heat water gains is highly proportional to the amount of solar input. The solar input is the irradiation (W/m^2) multiplied by the TES's absorbing area (m^2). Accordingly, the solar input could be enhanced by increasing the surface area of the TES. This would allow the system to heat water even at moderate solar irradiation.

The plots in Fig. 8 reveal that both water and tire crumbs, TES, are gaining heat in the morning, where their initial temperature is close to the ambient temperature. In the afternoon, the water outlet temperature increased (See Figs. 4 to 6) as water received heat from the solar input and the TES. The TES started discharging to water after 3:00 PM. After sunset, water heating continued as the tire crumbs continued discharging the stored thermal energy. At this point, the flow rate influences the water heating. The system continues to heat the water till 01:00 AM, 07:30 PM, and 06:00 PM for 10, 20, and 30 L/h water flow rates.

From the compact SWH design point of view, the flow rate and the TES surface area are important parameters to be considered. Also, increasing the residence time of the water inside the system can increase the system's performance and increase the outlet temperature. This increased residence time could be achieved by elongating the water passage inside the TES.

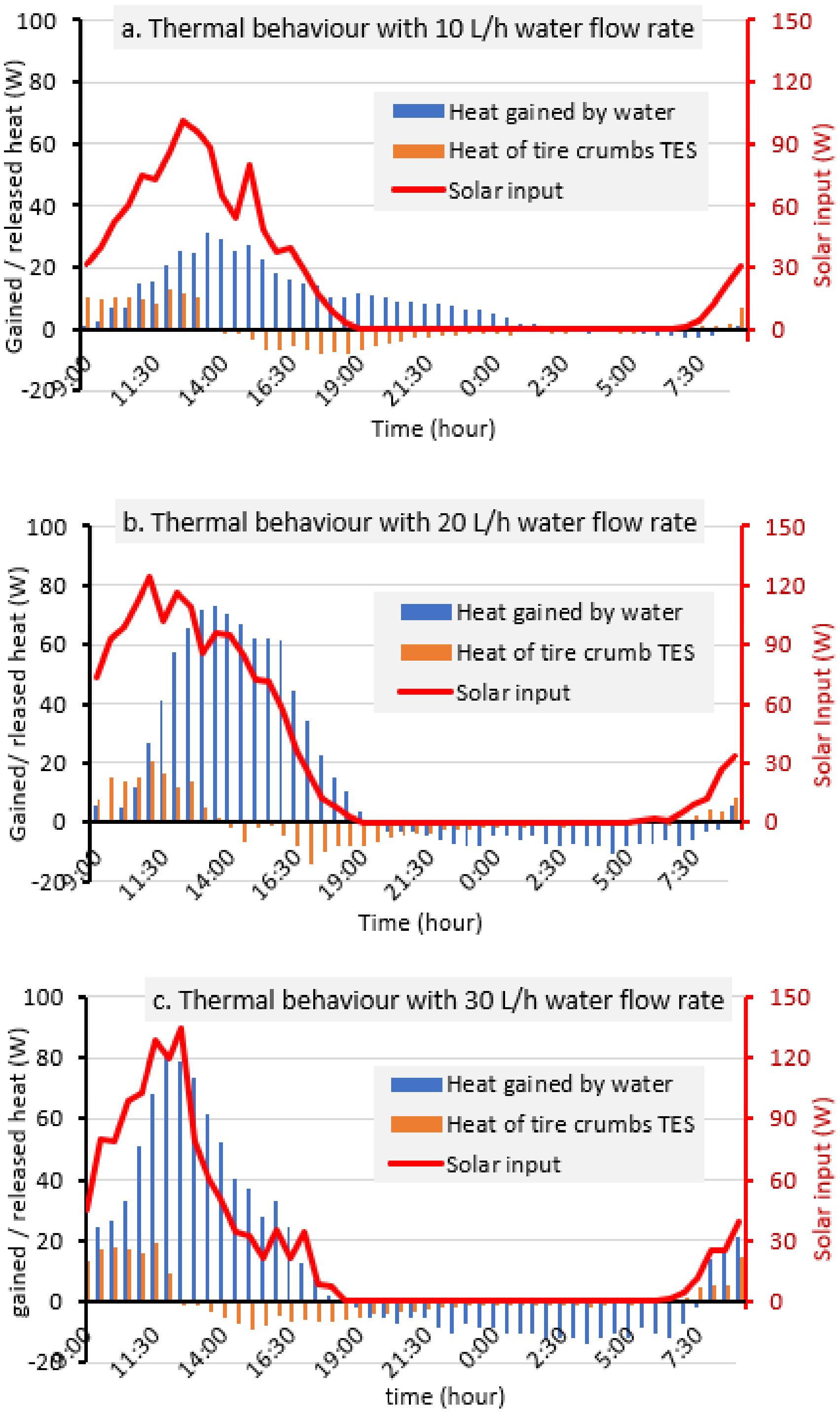

Fig. 9. Thermal behaviour of the compact solar water heater. a. at 10 L/h water flow rate b. at 20 L/h water flow rate, c. at 30 L/h water flow rate.

5. Conclusions

Using recycled tires and tire crumbs in energy applications is investigated experimentally. The usage of end-of-life tire crumbs in the current work is for solar-to-thermal energy conversion for water heating. The experimental work is repeated for two days by allowing water flow rates at 10, 20, and 30 L/h. The higher the water flow rate, the higher the achieved efficiency. The produced crumbs from recycled end-of-life tires have shown potential for solar photothermic and solar energy storage for heat discharge after sunset. The introduced technique is a promising for producing compacted solar water heaters on a small scale and on a large scale for industrial applications.

However, as this work is just a preliminary proof of concept of using recycled tires for energy application, there is much room for research to investigate further the system performance with a collector with a larger surface area and a longer water circulation system in a closed loop. Extending the application by investigating the compact solar water heater using mixtures of tire crumbs and latent or sensible TES materials is highly recommended.

Acknowledgments

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Nomenclatures

C_P	Heat capacity of the TES material, J/kg·K
m_{TES}	The mass of the tire crumbs, kg
$Q_{gain.wat}$	Heat gain by the flowing water, W
T	Temperature, ºC

Greek Symbols

$\eta_{thermal}$	Thermal efficiency

Abbreviations

ELT	End-of-life tires
SWH	Solar water heater
TES	Thermal Energy Storage

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