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Solar power harvesting with metal modified windshield glass to obtain hot water

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Abstract

Energy solar harvesting through low environmental impact resources is an underlying objective for future technological developments. In this work, an innovative design of a vitro-metallic composite material is developed with Cu^0, Zn^0 and ZnO microparticles dispersed in a glass-ceramic matrix. The uppermost feature of these materials is that they are made of the reused of vehicle windshield glass disposed. The vitreous composite performance is evaluated in different seasons and under diverse weather conditions. The energy absorption is analyzed from the results of the UV-Vis spectra and SEM images of the different composites. In this work it is demonstrated that the studied material has a good performance even in low temperature regions, reaching an efficiency between 30 to 50 [KJ/ KgH_2O] with a 0.3% wt of metal-modified glass-ceramic material in water. The material response was analyzed through the composite material UV-Vis spectrum. The new glass-ceramic materials are efficient in the process of heating water without the need of expensive devices or other forms of energy applications.

1. Introduction

Within the years, the care and preservation of the environment has become an important issue concerning the impact that human lifestyle and habits have on our planet. This concern has led to a new paradigm in the way energy is produced, and the way in which waste material is handled and disposed. An eco-friendly transition is taking place not only at big companies, but it has also become an everyday human habit. Despite such awareness more measures and actions are still needed to reduce the impact of waste mismanagement and disposal.

To address this concern, it is essential to know and to quantify the damage already generated. One way to do it is by studying the ecological footprint and the carbon footprint [1-4] which allow to dimension pollution, waste material amount and raw material consumption. It is also important to understand how the economic global model is affected by resources exploitation, fundamentally concerning those resources that are limited and have an impact on biodiversity. Since the industrial revolution during the XVIII century the technological production has followed the so-called linear economy, which nowadays has been proved to be the wrong way. A migration to the so-called circular economy (CE) is imminent. The linear economy (LE) was a model based on the disposal of products after their use, repeating extraction - production - disposition without worrying about the consequences, pursuing permanent economic growth only based on increasing consumption. Therefore, every product ends up as waste generating a heterogeneous mixture making separation process or material reuse almost impossible. That garbage is usually forgotten or destroyed in sanitary landfills, incinerators, or in any place without following any environmental rules or legislation. According to Barrett *et al*. greenhouse gas emissions have to be reduced up to 2050, where the industrial energy and emissions due to goods and services production, from the starting raw material through to the eventual disposal must be reconsidered under the circular economy new economical paradigm [5]. In this model, what was previously a waste now becomes a resource [6-7]. This economic model emerges as wealthy restructuration since its development should allow obtaining a competitive advantage in the context of globalization, generating greater competitiveness in the market and the development of innovative ideas that can lead to employment generation.

When thinking about the Sun as the undeniable great energy source, the relationship between the solar radiation and materials able to capture it become an outstanding opportunity in the seek of clean energy generation. Our planet receives from the Sun an amount of energy that is approximately 1.6 million kWh / year 40% of which is useful, that is several hundred times of the worldwide consumed energy. Thus, the energy consumption is conditioned by the intensity of solar radiation received by daily, annual cycles and weather conditions. Solar energy and its conversion to heat or electricity depends on the collector efficiency, defined by the relationship between the energy flow that reaches the material surface and the amount of energy that is transmitted to a fluid, which varies with the intensity of radiation, the temperature of the fluid in contact with the collector, the ambient temperature and the material used in the collector construction [8].

Regarding every concept previously outlined, we have studied the interaction between solar radiation and a new energy-collecting/energy-harvesting material obtained by the incorporation of metal nanoparticles and/or microparticles within a glassy matrix. The resulting metal vibrational energy is released as heat which is stored in the glass and transferred to the water [9]. Photons absorption on those metal particles involve a heating effect due to metal electrons moving and as their optical performance is poor (they are very poor light emitters) the total amount of heat generated can be released as heat allowing the rise in the surrounding medium temperature [10-11]. To cover all the concepts outlined before and to propose an innovative reuse of vehicle windshield glass [12-13], a waste of excellent quality due to its almost invariant chemical composition, we designed a simple method to transform it in a glass ceramic (metal-glass) which exposed to the solar radiation allows to store energy in the form of heat. The material performance depends on the glass-ceramic composite morphological and chemical characteristics. The proposed methodology does not involve the use of organic solvents, minimizing the waste volume and water consumption. Also, the manufacturing process does not require large energy consumption [14-17].

2. Experimental

Pilkington [18] brand windshield glasses and clear glasses of food containers were used. Initially they were washed to remove dirt. Next, they were manually broken into large pieces and the polymer that is part of the windshields glass was manually removed. Then, it was mechanically ground to a fine powder with a ball mechanical milling.

Figure 1: Windshield glass and clear glasses of food containers used.

The glassy powder was sieved to remove larger residual particles. Mixtures with Cu^0 powder, Zn^0 powder and ZnO powder were prepared to 1% by weight, using analytical grade reagents (Cu M3N – Ventron; ZnO: Cicarelli; Zn: Cicarelli). Stainless steel rings were placed on a plate of the same material (as a mold) and were subjected to a heat treatment in a muffle with a regular atmosphere at 750 ° C for 30 minutes. Then, the samples in the mold were remove from the muffle and put on a hot plate at 200 ° C for one hour to relax the mechanical stress. The modified glasses samples are shown in figures 2.

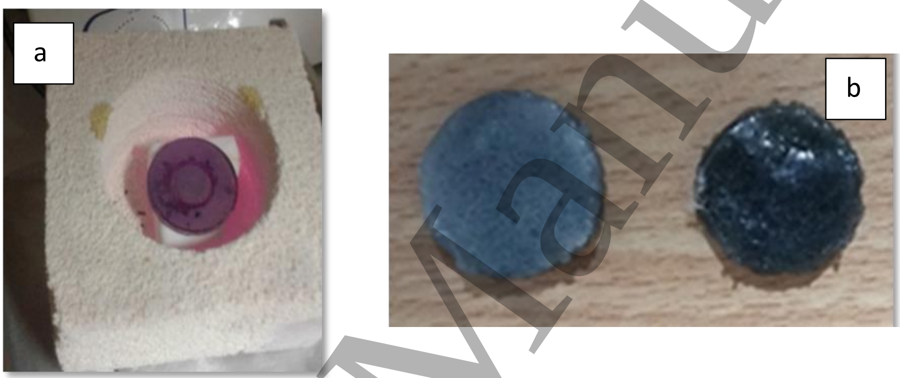


Figure 2: a) Stainless steel rings and plate (mold) used for thermal treatment in muffle. b) Modified glasses samples, as example (bottle glass on the left, windshield glass on the right).

Optical absorption study was carried out at room temperature using an Agilent Carry 60 UV-Vis spectrometer between 200-800 nm wavelength range. Samples were polished to obtain thin disks with parallel faces of around 0.7mm thickness and smooth surfaces. SEM images were obtained with microscope SEM EVO 40 XVP.

3. Results and discussion

3.1 Data register

Measurements of solar energy capture were made in Alpachiri town (La Pampa- Argentina). Figure 3 shows the Alpachiri's location, a small town located at the east of La Pampa, Argentina.

It has approximately 2,000 habitants and the area is described as subhumid characterized by an average annual temperature of 15°C (24°C maximum annual average in January and 7°C minimum annual average in July). However, it is worth to mention that the absolute summer values could exceed 42°C while, in winter temperatures down to -14°C could be recorded. According to the rainfall records (from 1921 to the present) the historical average is 662 millimeters per year with a seasonal distribution of 34.7% in summer, 34.5% in spring, 16.6% in autumn and 14.2% in winter [19]. Meteorological data was taken from Meteobahía page [20] which is governed by CONICET (Atmospheric Sciences) [21] and INTA [22].

Figure 3: Alpachiri town (La Pampa- Argentina). Alpachiri's location, located at the east of La Pampa, Argentina; Datos del Mapa ©2021 Google).

3.2 **Location of samples and measurement procedure**

Data were gathered during four months (from February to May), three days a week randomly and eleven measurements by day. In this way, many different weather conditions (sunny, rainy, cloudy, windy, and stormy), from the sunrise to the evening, were analyzed. First, every glass sample (bottle and windshield) was tested in different places. 1.5g of glass sample was located into a Styrofoam container of total volume = 800 mL which contained 500 mL of distilled water (equivalent to 0.3% wt of metal-modified glass-ceramic material in water) and it was covered with a plastic film (avoiding surface wrinkles) to prevent the loss of water by evaporation. To determine the water temperature a thermocouple (K type) was introduced through a small hole which was always sealed by a sticky tape [23].

Figure 4: Glass samples in Styrofoam container covered with a plastic film. Thermocouple (K type) used to determine the temperature.

First, to determine if the efficiency of windshield glass is higher than standard glass (bottle glass in this case), we compared the effectiveness of heat absorption in water along the daytime and with different weather conditions. Figures 5 a, b and c show the energy absorbed (Q [KJ / Kg H_2O]) by the water as a function of the daytime in comparison to the solar radiation reported by Meteoabahía [20]. The obtained results allow showing that the windshield glass has a better performance given the chemical composition since the metal cations present in such glassy matrix make favorable the energy absorption, which is 20 to 30% higher than the amount obtained in the case of the bottle glass, even during the cloudy time.

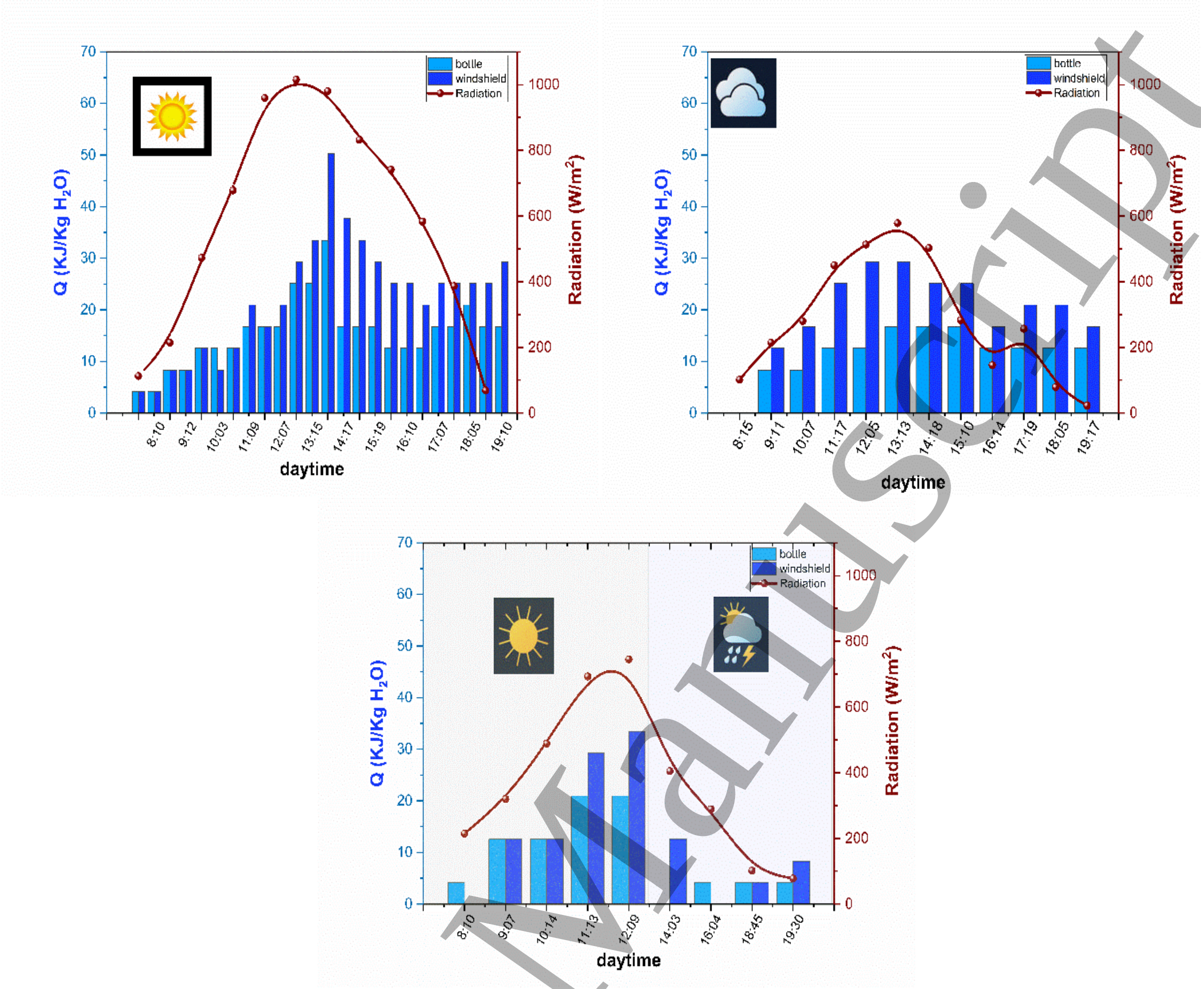


Figure 5: Energy absorbed by water (Q [KJ / Kg H_2O]) as a function of the daytime (bars). Solar radiation as a function of the daytime (red line) during sunny and cloudy time.

Therefore, to confirm the observed behavior we took the same data for four months. Figure 6 shows 1000 data for both glasses during sunny and cloudy days as a function of the solar radiation reported.

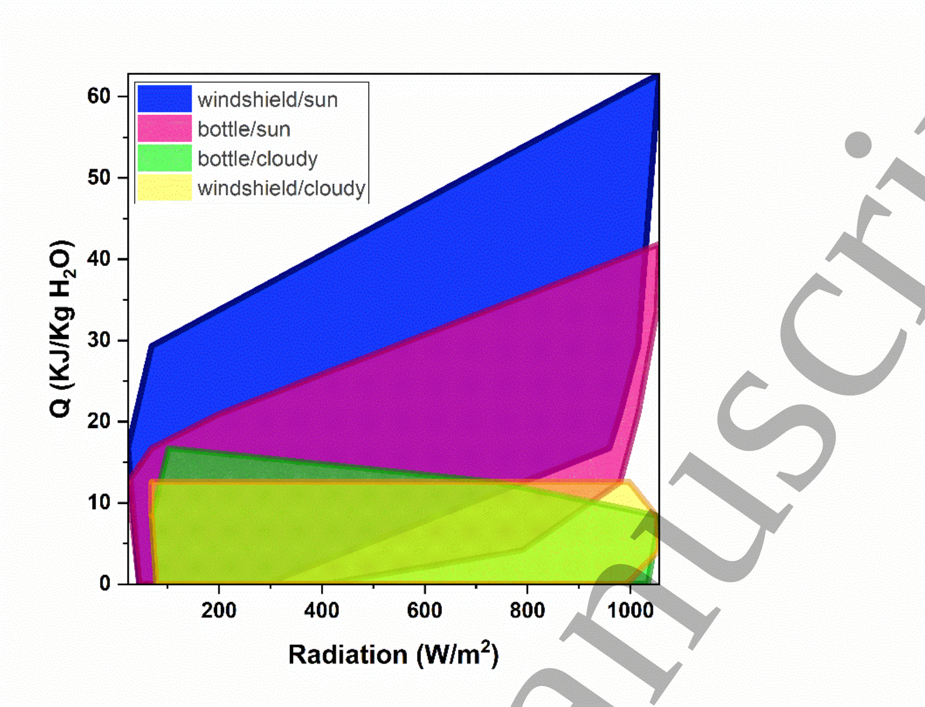


Figure 6: One thousand data gathered for both bottle and windshield glasses during sunny and cloudy days as a function of the radiation power.

From these results we assume that the windshield glass is more efficient than the bottle glass. Therefore, the following step was to modify that glass by using the set of metals and oxides previously chosen as it was explained before.

Consequently, two groups of samples were prepared using four containers: 1) reference windshield glass, 2) windshield glass. ZnO, 3) windshield glass. Zn^0, 4) windshield glass.Cu^0. Each one contained 500 mL of distilled water. One group was kept under the sun and the other under the shadow [23]. Again, 1000 data were taken for each glass composition.

Figure 7: Samples group under the sun and under the shadow.

Next, we compute the temperature variation in each container [ΔT = water temperature$_{glass\cdot metal}$ - water temperature$_{glass}$] and finally, the net energy absorption due to the modification process was calculated as follows:

$$Q = m_{H2O}.C_{p\ H2O}.\Delta T \qquad (1)$$

where: Q is the absorbed energy (J), m is the water mass, Cp is the specific heat at a constant pressure (4.186 J/g°C). Next, every Q value is expressed in KJ/Kg$_{H2O}$ and plotted in figure 8.

The results presented in figure 8 where the x-y plane presents the ambient temperature as a function of the solar radiation reported (all the data is the same for each modified glass) and the net energy absorbed by the water -for each modified glass- is presented through a color scale as it is indicated in the plot legend. The most important finding in the present work resulted to be that the modified windshield glass response depends on the solar radiation and on the ambient temperature as it was expected but, and more important, it strongly depends on the glass modifier incorporated. Surprisingly, the glass modified with Zn^0 seems to have better performance than that modified with Cu^0. On the other hand, the glass modified with ZnO is less efficient. Such behavior confirms that the modification with metal microparticles has a greater effect on the heat absorption efficiency than the nature of the cations in the glassy matrix, even those that has absorption in the UV spectrum region, as we explain after. Even more relevant, it is that the behavior of the glass modified with Zn^0 shows a better performance at lower solar radiation and ambient temperature than the glass modified with Cu^0, since the higher Q values spread over a larger area (orange zone (15KJ/Kg H_2O) in figure 8 b). However, at higher solar radiation and higher temperature values the glass modified with Cu^0 reaches even higher Q values (red zone (20KJ/Kg H_2O) in figure 8 a). From such results we conclude that depending on the environmental conditions a class of these materials could be chosen.

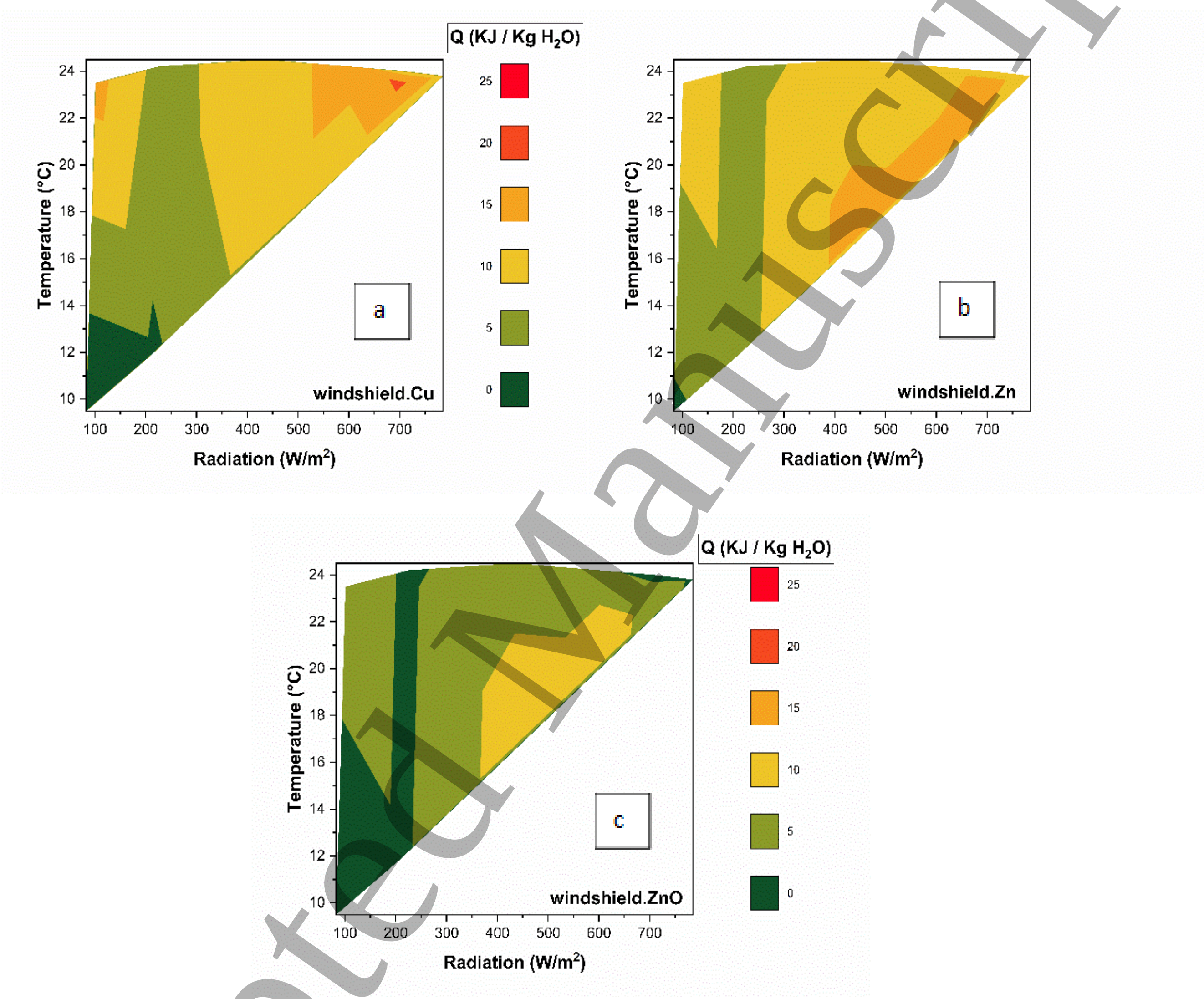


Figure 8: Q values obtained for each modified glass is plotted on a X-Y plane given the ambient temperature as a function of the solar radiation reported. The net energy absorbed Q by the water is presented through the same color scale for all as it is indicated in the legend.

a) Windshield glass. Cu^0, b) Windshield glass. Zn^0 and c) Windshield glass. ZnO.

Therefore, to explain the observations listed above we characterized each modified glass through the UV-Vis spectroscopy technique.

3.3 **UV-Vis characterization**

Each sample was polished to obtain thin disks with parallel faces of around 0.7mm thickness and very smooth surfaces. Optical absorption analysis was carried out at room temperature using the spectrometer between the 200-800 nm wavelength range.

Figure 9 shows the UV-Vis spectrum of each modified glass compared to the raw windshield glass. From this figure it is possible to learn that each modified glass absorbs more energy in the whole range between 200-800 nm than the raw windshield glass. However, a stronger absorption appears below 350nm, *i.e.,* in the UV range for each modified windshield. Now, if we compare among the different modifiers it is possible to explain the results presented in figure 8. Both metals, Zn^0 and Cu^0, have a strong band bellow 250nm while for ZnO, the strong absorption band appears at around 275 nm.

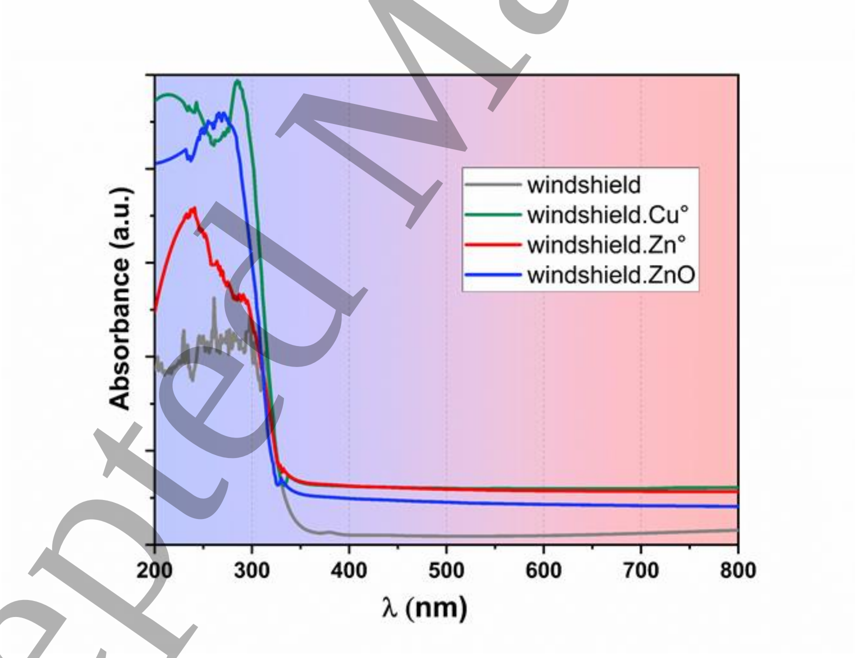
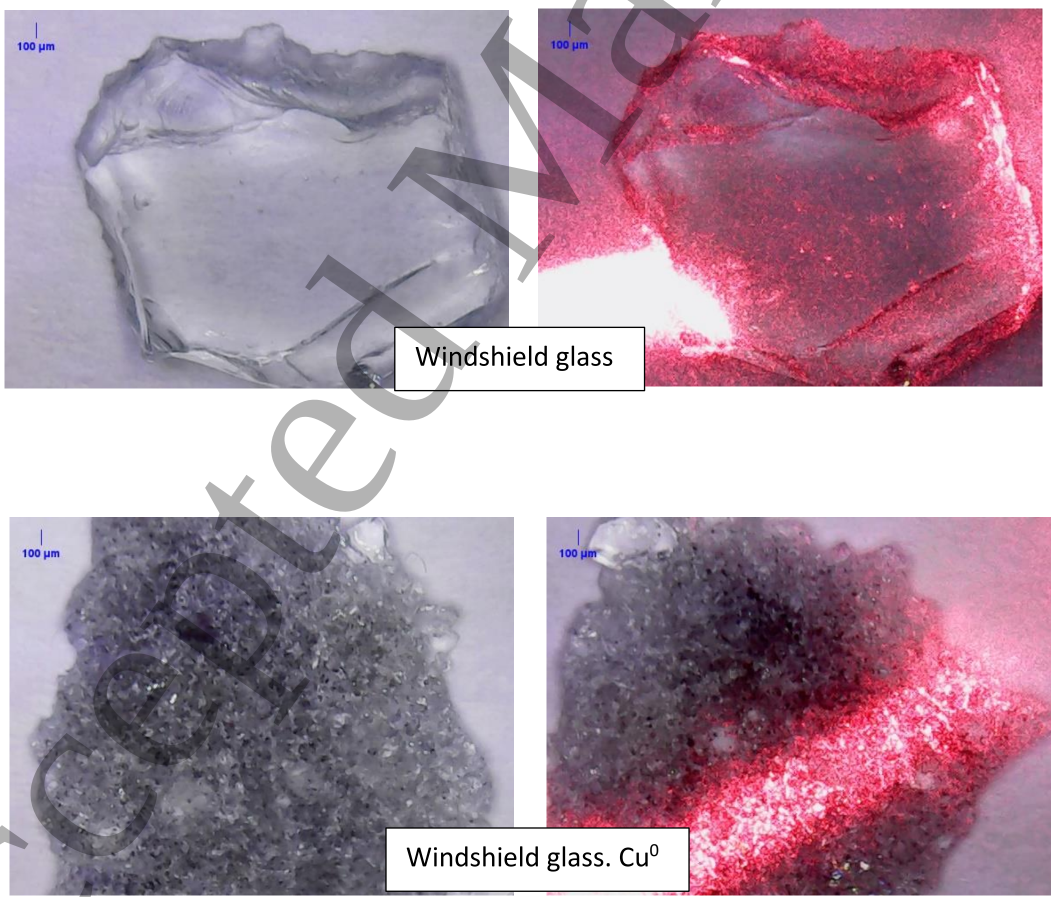


Figure 9: UV-Vis spectrum of each modified glass compared to the raw windshield glass.

Therefore, from the UV-Vis spectra it is possible to understand that the three modified glasses behave as energy solar captors. However, the use of metal microparticles boosts the amount of captured energy that can be transferred to water as a result of the metal vibration phenomena [8-11] explained before in the introduction, making the solar energy harvesting more efficient.

Finally, to reinforce this interpretation we observed the interaction between the modified glasses with a red laser beam. Figure 10 shows the optical microscopy images with a 1000x magnification (digital microscopy). Those images reveal that this beam interacts with the glass ceramic morphology. The presence of the metal microparticles is clear through the bright spots in modified matrices. Those microparticles are responsible for the high energy absorption shown by the UV-Vis spectrum stronger for shorter wavelength values, even in the case of nonmetallic particles like ZnO as is expected for this oxide. Therefore, such results allow us to confirm that is the metal vibration the responsible phenomenon to develop the material appropriate for solar energy harvesting to be transformed in heat directly.



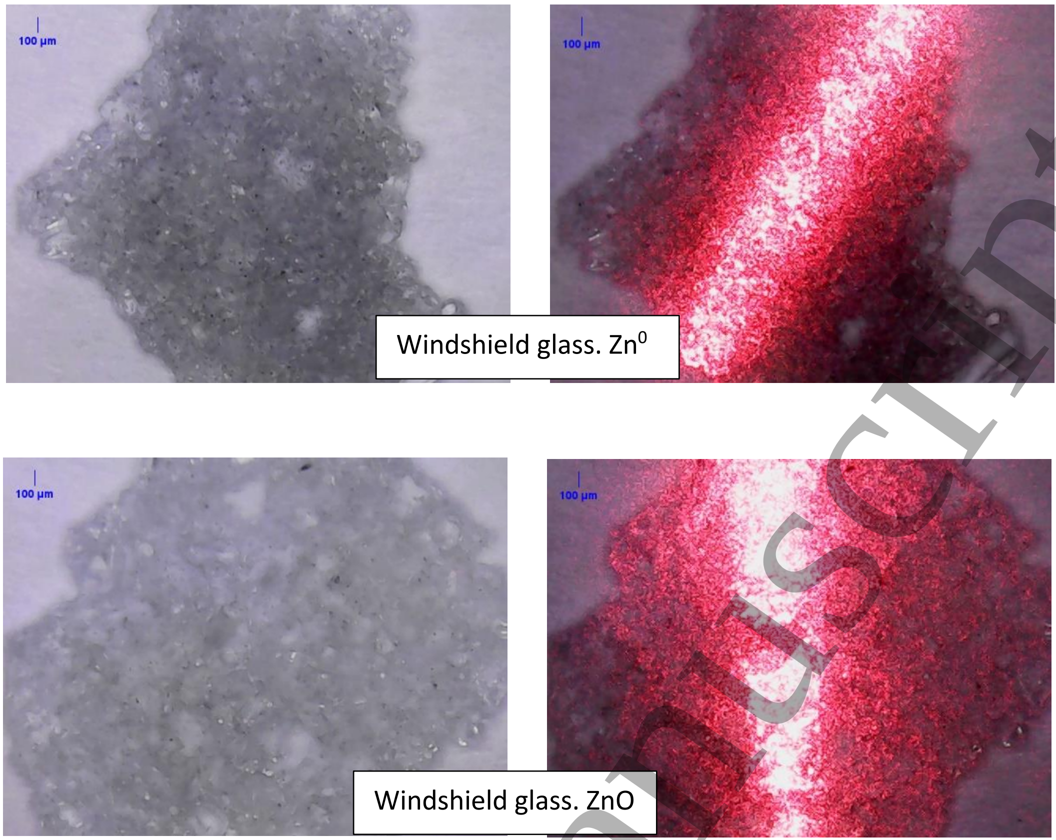


Figure 10: Optical microscopy images (1000x digital microscopy) where the red laser beam interacts with the glass ceramic morphology (right) comparing to the sample under the natural light (left). These images are presented with the purpose that the particles dispersion and the appearance of the material by the mere contrast with the laser considering the laser has a very low power (10mW).

However, it is acceptable to expect that to some of the metal particles can oxidize, mainly on the surface because the contact with the atmosphere. To avoid such problem, each sample was polished before observing and studying. However, as we can approximate from the comparative behavior presented, while ZnO tends to mix in the glassy matrix as the SEM microphotograph reveals (see figure 11) while the metallic particles (Cu^0 and Zn^0) tend to remain, at least to a certain proportion, as such (see figure 11).

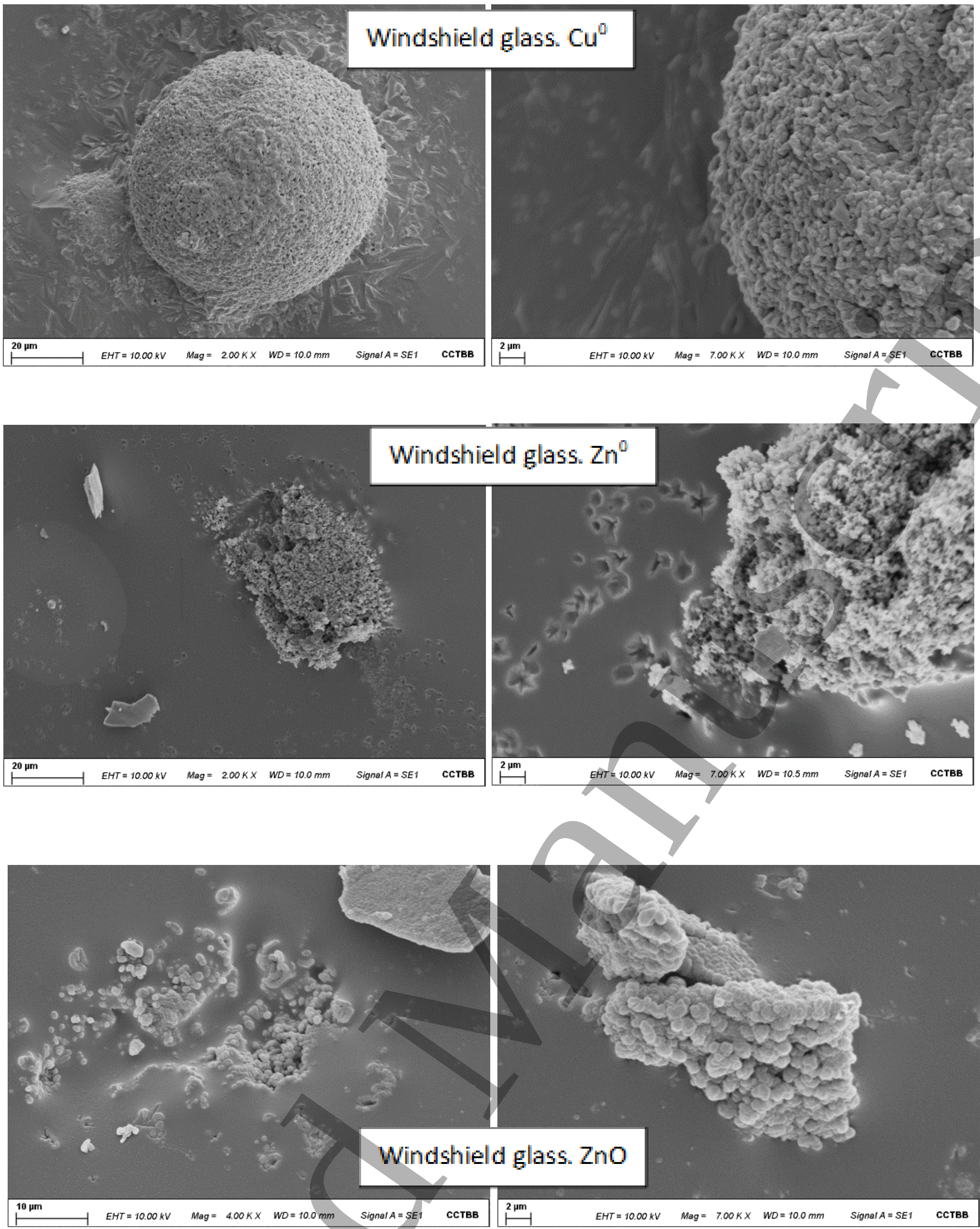


Figure 11: SEM images: Windshield glass. Cu^0 (top), Windshield glass. Zn^0 (middle) and Windshield glass. ZnO (bottom).

4. Conclusion

In this work, an innovative method to reuse vehicle windshield glasses was developed in the context of circular economy. Such glasses are generally wasted and dumped in sanitary landfills at the end of their lifetime. Composite materials were designed as modified glass-ceramic matrices by incorporating metallic microparticles. The performance of those new materials as solar energy collectors was evaluated during different seasons and in various weather conditions. The material response was analyzed through the composite material UV-Vis spectrum. It was shown that both, copper, and zinc incorporation as metallic microparticles dispersed in a glass-ceramic matrix, lead to the development of materials that are efficient in the process of heating water without the need of expensive devices or other forms of energy applications.

Note: photos 1, 2,4 and 7 were taken by the authors.

Acknowledgements

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