JOURNAL OF CHEMICAL EDUCATION

Luminescent Solar Concentrators from Food Substances: A Safe and Simple Experiment to Approach Sunlight Energy Harvesting

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Cite This: *J. Chem. Educ.* 2023, 100, 4559−4566

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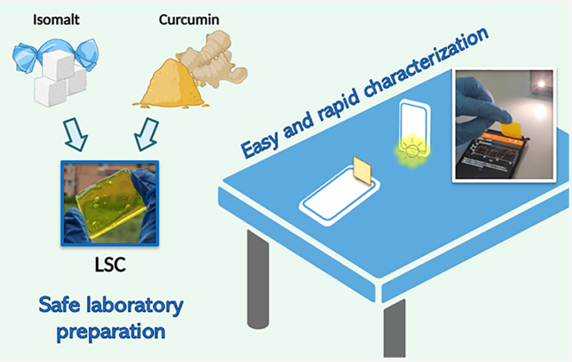


ABSTRACT: Safe and visually appealing experiments can help the general public, even from a young age, to better understand the fundamental role of chemistry and materials in the energy transition and our everyday lives. Luminescent solar concentrators (LSCs) are efficient devices for harvesting sunlight based on the fluorescent compounds' properties. They constitute an exciting demonstration platform to engage audiences because of their coloration, intriguing interaction with light, and relevance toward the UN sustainability goals. While LSCs are usually made of transparent plastic and fluorescent dyes, in this study, they were fabricated employing only ready-available common food materials, such as isomalt, an amorphous sugar, and vitamin B2 or curcumin as edible fluorophores. This makes the fabrication procedure remarkably safe and rapid without affecting the final LSC's performances, which were comparable to other state-of-the-art devices. Furthermore, a simple and rapid characterization of LSC was developed for qualitative performance determination and required only two smartphones. The gathered results render this approach appealing to design interesting dissemination experiments where the participants can explore the phenomenon of fluorescence and understand the principles behind functional real-world applications such as LSCs. In this sense, this demonstration offers an interesting take to discuss one of the many roles of chemistry in the energy transition.

KEYWORDS: *Outreach, Demonstration, Hands-On Learning, Applications of Chemistry, Materials Science, Natural Products, Fluorescence, Luminescent Solar Concentrators*

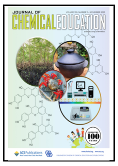
■ INTRODUCTION

Presently, newer generations are showing an ever-growing interest in sustainable development, becoming effectively aware of the dangers caused by global warming.[1] Most young people are actively trying to waste less water and energy[2] to make more use of public transport over cars and reduce animal product consumption to limit the environmental impact of breeding farms.[3] Despite this drive to take care of our planet, one does not observe great passion for chemistry and materials science in these generations.[4]

As enthusiasts of the discipline, we feel a responsibility to communicate it effectively and engagingly. Of course, school is a place where interest in chemistry can be stimulated,[5,6] together with social media communication[7] and demonstrations targeted to broader audiences. For either classroom or remote learning, simple and safe experiments can offer an attractive platform to combine theoretical principles and practical applications. Integration of visually appealing elements can increase the effectiveness of these demonstrations, regardless of the target audience. Among the different possibilities at one's disposal to achieve such a goal, fluorescent materials can be beneficial thanks to their intriguing interaction with light.

The phenomenon of fluorescence can be helpful in explaining the interaction between light and matter. However, it could also represent a fascinating and timely example of the use of chemical systems to achieve sunlight concentration and boost the performance of photovoltaics in the urban environment.[8] In particular, luminescent solar concentrators (LSCs) are devices in which an organic luminophore is usually embedded in a waveguide.[9] As illustrated in Figure 1a, the luminophore molecules absorb sunlight photons and re-emit them at longer wavelengths through fluorescence. Because of the refractive index mismatch between the device and the surrounding air, the polymer or glass matrix traps the emitted photons into the device and focuses them on the edges by means of total internal reflection (TIR). A photovoltaic (PV) cell, coupled to the edge of the LSC, converts emitted photons into an electric current.

Received: July 21, 2023
Revised: October 3, 2023
Published: October 23, 2023



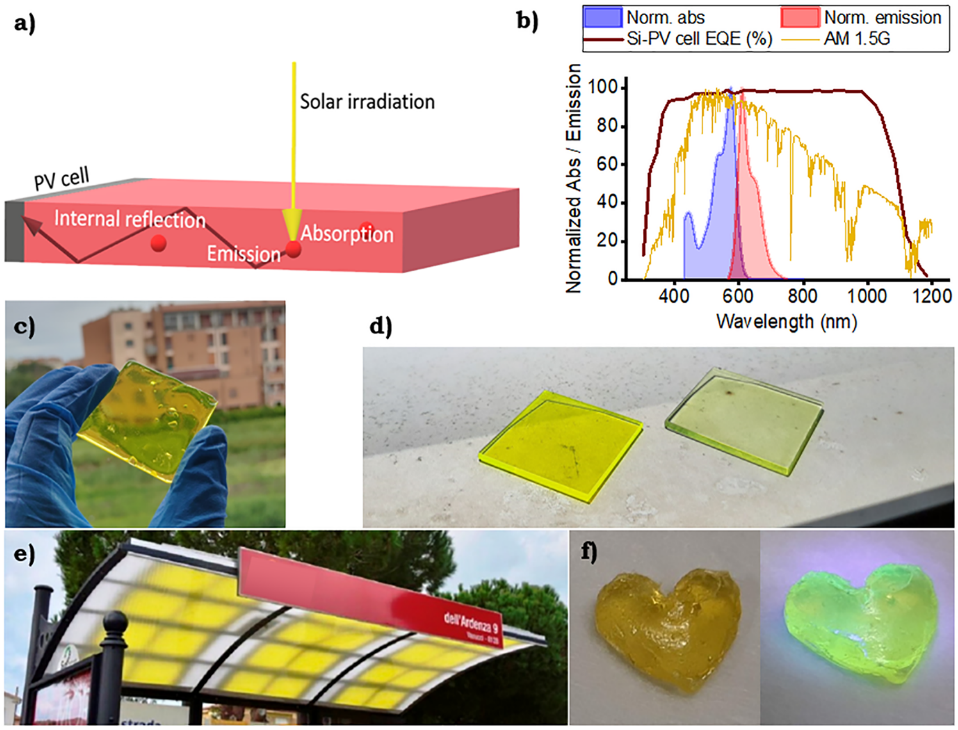


Figure 1. a) LSC working scheme; b) compatibility of the solar spectrum with the absorption spectrum of a state-of-the-art fluorophore (Lumogen F Red 305), and its emission spectrum of the latter with the EQE (%) of the Si−PV cell; c) photographs of a slab LSC of PMMA and a PMMA thin-film LSC on glass comprising a yellow fluorophore; d) photographs of isomalt-curcumin LSCs highlighting their transparency and emission features; e) LSC bus shelter installation in Livorno, Italy;[21] and f) heart-shaped curcumin-isomalt mixture prepared by a high school student under room illumination and under UV illumination with a flash light.

LSCs are usually produced as a slab of a glassy polymer with the fluorophore efficiently dispersed within or as a thin film applied on a glass substrate with high optical purity (Figure 1c). The PV cell is placed on the edge of the glass so that the emitted photon can exploit the entire volume (sum of thin film and substrate) as the waveguide. An ideal fluorophore should have high photoluminescence quantum yield (PLQY) and a broad absorption spectrum in the visible range, where the sunlight has the highest optical density (Figure 1b).[10] The optimal waveguide has an amorphous character, with high transparency in the visible range and a refractive index of 1.5−2.0, to limit reflected light and improve light concentration.[11] Poly(methyl methacrylate) (PMMA), a commodity plastic, is usually employed as polymer matrix for LSC.[12−14]

In the near future, foreseeing a significant increase in electricity demands, especially in cities, LSCs will be a promising technology for several reasons:[15] (i) they are fabricated employing inexpensive materials, allowing them to cover large-area surfaces such as urban facades at a low cost; (ii) their use limits the exploitation of critical raw materials, requiring only minimal quantities of photovoltaic modules; and (iii) thanks to their semitransparency and bright coloration, LSC can be installed to well integrate with the aesthetics of a building. Furthermore, LSCs are not markedly orientation-dependent, i.e., they can work in direct and diffuse light, allowing for higher cost-effectiveness than silicon PV cells at disadvantageous angles, which is usually the case in urban environments.

LSCs technology has demonstrated that it can overcome the daily performance ratio of directly illuminated silicon photovoltaic modules,[16] which is why there have been several examples of LSCs installation in recent years.[17−21]

In this paper, we show how to fabricate LSCs with remarkable light concentration performances, employing only common food materials, which can be obtained from a supermarket. In particular, we employed isomalt as waveguide material and natural fluorophores as active components. The former consists of an approximately equimolar mixture of α-D-glucopyranosyl-1−6-sorbitol and α-D-glucopyranosyl-1−6-mannitol[22] and it finds use in the food industry as a sugar substitute for cake-sculpting and decorations. Thanks to its transparency and refractive index of around 1.63, an isomalt-based LSC ideally traps 79% of the emitted photons.[23] In the case of PMMA, typically used in LSC applications, this value is 75%. Concerning the active optical component, we wanted to investigate food substances capable of showing fluorescence, which could be obtained readily from a supermarket or on the Internet (Figure S1 of the Supporting Information, SI). In this regard, we tested riboflavin, also known as vitamin B2 and curcumin.

In addition, we show how it is possible to characterize the LSC performances employing simple and available tools, such as photodiodes, available at specialized hardware stores, or even the illumination sensor included on most smartphones, intended for autoadapting screen brightness features. Remarkably, the obtained results were qualitatively similar to those we collected for the state-of-the-art characterization of the same devices employing ad-hoc laboratory equipment and much faster to perform (less than 5 min). Overall, both the fabrication and characterization procedures of the proposed isomalt-based LSCs can be carried out with minimum risk in school laboratories and even at home. They allow the design of risk-free demonstrations and visually appealing experiments to explore the light−matter interaction and to introduce the discussion on the roles that chemistry can play toward the sustainability goals.

MATERIALS

Isomalt (Bongiovanni s.r.l., Italy) and silicone molds (SourceTon, China) were purchased at Amazon.it. Riboflavin, curcumin, and quinine were obtained from Merck Life Sciences s.r.l. (Italy) and used as-received. Curcumin as a food coloring agent E100 (Disano, Italy) for the home experiments was purchased at a local supermarket.

PROCEDURE

For the fabrication of the LSCs, we employed an isomalt mixture comprising the fluorophores at different concentrations (0.001 wt % to 0.1 wt %). To start, a 0.1 wt % mixture (i.e., 1 mg fluorophore/g isomalt) was prepared by melting 10 g of isomalt in a crystallizer over a hot plate at 130−150 °C (temperatures above 150 °C slowly cause the isomalt to darken) under stirring. Ten mg of the fluorophore was added, and the isomalt was stirred until complete dissolution. Placing the vessel under vacuum (50 mbar) during the melting and mixing process or continuous slow stirring reduces the presence of air bubbles. The 0.1 wt % mixture was employed to prepare 5 g batches of mixtures at lower concentrations by melting it together with the adequate amount of pure isomalt. Finally, the LSC slabs of dyed isomalt were prepared by transferring the latter mixtures in square cooking-grade silicone molds (2.5 and 10.5 g of mixture to fabricate $3 \times 3 \times 0.2$ cm^3 and $5 \times 5 \times 0.3$ cm^3 LSC, respectively) and melting them again to obtain smooth flat surfaces. Isomalt LSCs are hygroscopic and tend to absorb water over days, making them opaque. If not used the same day, then we advise keeping them in a desiccator. Nevertheless, an opaque LSC can be melted again to regain its typical transparency.

A state-of-the-art determination of the LSC's optical properties and photonic efficiencies was performed following recently published laboratory protocols.[24,25] The LSC's device efficiency was eventually determined by connecting two Si−PV cells in series to one edge of the LSC using silicone grease (reported in detail in the SI.

Light intensity measurements employing two smartphones were performed using the torch of a Realme X50 Pro smartphone as light source (the spectral emission is reported in Figure S2), positioned about 10 cm from the LSC. The LSC was placed vertically with the edge resting on the brightness sensor of a Samsung Galaxy A50 smartphone (model TCS3701, AMS OSRAM), acting as a detector. A black cardboard mask was used to isolate a 1×1 mm^2 section on top of the sensor. Data were collected in real time with the Phyphox app,[26] currently available on Google Play and the App Store. The result was reported as the average of the emission intensities acquired on each edge divided by the same measurement performed on a pure isomalt slab.

The edge-emission characterization employing a photodiode was performed using a 1×1 cm^2 photodiode (THORLAB FDS1010 Si). In order to only measure the light coming from the LSC, the photodiode was shaded with a piece of black cardboard comprising a slit of 1×9 mm^2 over which the LSC was placed (see SI). The photodiode was connected to a digital multimeter (DT-5808) to measure the current output, and the LSC was irradiated using the same smartphone mentioned above from a height of 6 cm (see SI). The concentration performances of the LSC were reported as the ratios between the current obtained from the dyed slab over the pure-isomalt slab.[27]

HAZARDS AND WASTE DISPOSAL

Isomalt, curcumin, and riboflavin are not hazardous substances. However, all operations should be conducted wearing protective goggles, safety gloves, and a protective coat to prevent dyes from staining hands and clothes. The heating plate should be handled with care to avoid burns or electric fires. Molten isomalt can cause burns and should be handled with care. Isomalt in its glassy state, when broken, can be slightly sharp. Waste materials should be treated as lightly contaminated solid waste and disposed according local regulations. Isomalt is considered an ignitable material. When using smartphone flashlights, UV flashlights, or sunlight during the characterization, avoid looking into the light sources.

RESULTS AND DISCUSSION

The choice of food substances can offer several advantages for the design of educational experiences. First, and most importantly, these materials are inherently safe to handle and, as such, they can be used in almost any scenario, including experiences targeted to young kids and homemade experiments. In most cases, one can obtain the necessary materials easily, either from a supermarket or online, without restrictions. In addition, such experiments give a positive image of chemistry as a science aimed at energy efficiency and sustainability, which may increase its appeal,[28,29] and, especially when shown side by side with the real devices, versions fabricated employing common food materials can be exciting and eye-catching.[30]

Nonetheless, these materials may suffer limited performances when compared to the state-of-the-art devices.[31] To investigate whether the combination of isomalt with riboflavin or curcumin is suitable to prepare functioning slab LSCs, we fabricated several samples comprising various quantities of fluorophores to isomalt. Given its long-known emission properties, we have also tried quinine as an edible fluorophore during preliminary tests.[32] Unfortunately, quinine did not show sufficient solubility in isomalt and seemed to speed up the degradation of isomalt at melting temperatures. Moreover, it absorbs photons only in the UV region, which is not optimal for LSC applications (only 4% of the sunlight is UV radiation).[33]

Since isomalt is commercialized in its crystalline form, it was melted at over 120 °C in an appropriate container so that it can be stirred efficiently. Adding riboflavin or curcumin to the molten isomalt resulted in homogeneous mixtures. Finally, glassy LSCs made of amorphous isomalt were obtained by air-cooling in flexible silicone molds, as the high viscosity slows down the crystallization.[34,35] In particular, we prepared $3 \times 3 \times 0.2$ cm^3 samples with 0.005−0.1 wt % concentrations of riboflavin and 0.001−0.1 wt % concentrations of curcumin. These samples were highly transparent and, especially in the case of curcumin, emitted noticeable light from the sides, as expected from LSC devices (Figures S3 and 1c). The transmittance spectrum of an isomalt slab is shown in the SI

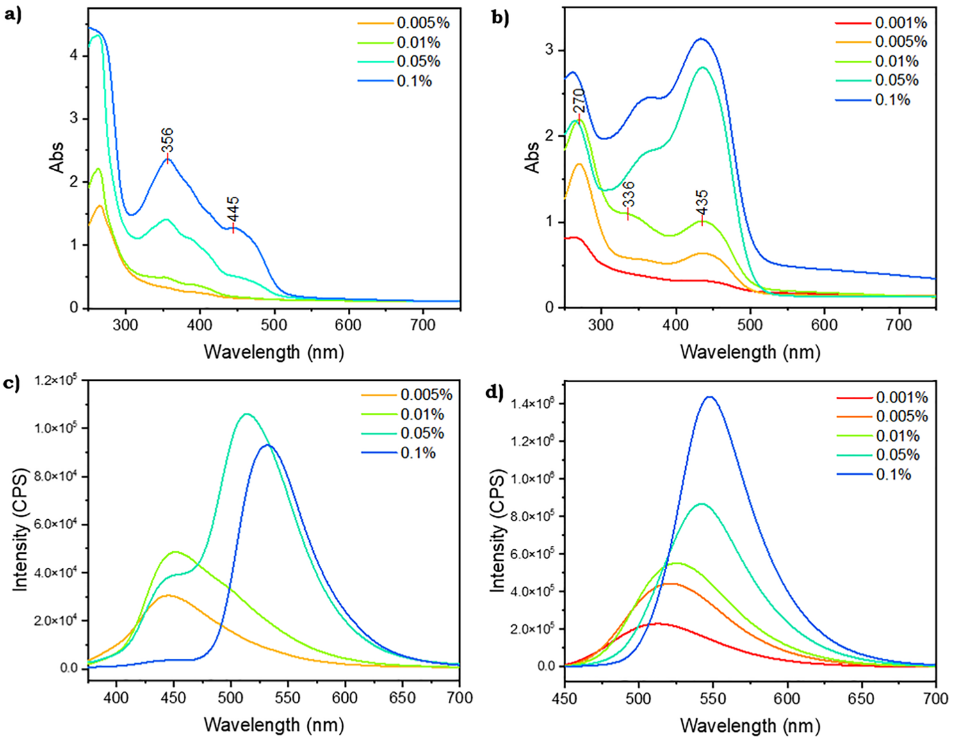


Figure 2. UV−vis spectra of the isomalt LSC containing: a) riboflavin, b) curcumin; fluorescence emission spectra of the isomalt LSC containing: c) riboflavin, d) curcumin as a function of the fluorophore content (wt %).

to highlight its inherent transparency, ranging from 65% to 77% in the visible for a 2 mm thick sample (Figure S4).

For the preparation of standard LSCs, surface areas greater than or equal to 5 × 5 cm^2 are usually preferred to facilitate interlaboratory comparisons and a more meaningful estimation of their performances. In any case, real-world LSC installations involve large-area devices, which ideally have larger geometric gains and thus are characterized by greater concentration effects and efficiencies (see Supporting Information).[36]

To understand whether these materials are suitable for preparing LSCs, students can experience the use of UV−vis and fluorescence spectroscopies. The spectrum analysis can be helpful to focus on the different energy of photons of different wavelengths, and to gather information on their usefulness in energy harvesting. In fact, students need to understand the rationale behind the choice of fluorophores, including the overlap between their absorption and solar spectra (Figure 1d).

Moreover, the external quantum efficiency (EQE) of the photovoltaic cell, which measures the activity of the cell concerning the wavelength of the incident photons, can be compared to the emission spectrum of the fluorophore to verify the best match in terms of efficiency (Figure 1b). In this sense, for a performant LSC, a suitable fluorophore-matrix mixture should be characterized by a large overlap between its absorption profile and the solar spectrum and display a strong emission.

By preparing LSCs at different concentrations, students can appreciate the relationship between sample absorbance, optical path, and chromophore concentration. It is worth noting that deviations from the Beer−Lambert equation are common in these systems, given that scattering effects and absorbances are often higher than 1. Teachers can guide students in comparing fluorophores, highlighting the ability of a molecule to absorb light at a specific wavelength (i.e., molar extinction coefficient) and how absorption affects the final color of the object. As shown in Figure 2, the absorbance values grow with increasing concentration in both cases. The main absorption peaks of riboflavin in isomalt are centered at 356 and 445 nm, with the former more intense than the latter and similar to the values found in the literature.[37] Curcumin absorbs mainly around 435 nm,[38] where sunlight is more intense, and it is characterized by a larger extinction coefficient, thus making this compound more suitable for absorbing sunlight.

With regard to fluorescence, students can observe the different tendency of molecules to exploit intense emission and compare the shape and position of emission and absorption peaks, thus obtaining hands-on evidence of nonradiative decay. As shown in Figure 2, curcumin in isomalt displays much higher emission intensities than riboflavin, with broad peaks from 450 to 600 nm. We believe that other more specific effects observed, such as the red-shift of the emission peaks with concentration and its change in shape in the case of riboflavin, are of a higher level of detail and thus beyond the educational scope of the experiment[31,39−45] (see SI).

As part of a thorough characterization of the fluorophores and the isomalt-based LSCs, we measured the PLQY to investigate the ability of riboflavin and curcumin to perform efficient emission in the isomalt environment (Figure S5).

Among the different fluorophores, only curcumin displayed a sufficient PLQY for practical applications (24.8%), since it can re-emit almost one-third of the absorbed photons, whereas riboflavin is less than 4%. As detailed in the SI, this parameter drastically affects the LSC performances, especially in the case of fluorophores characterized by a small Stokes Shift. For this reason, despite the noticeable fluorescence of riboflavin in isomalt, we find the isomalt-curcumin system to be more relevant for the application as LSC. We thus evaluated the performances of the isomalt-based LSCs as device efficiency

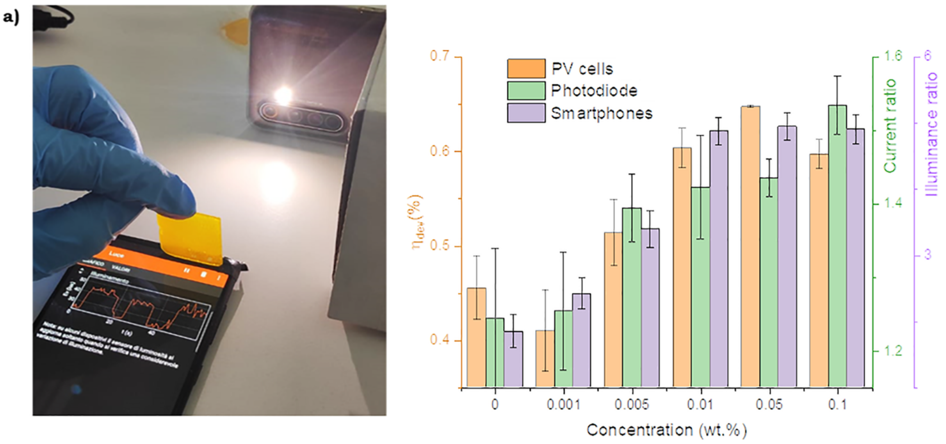


Figure 3. a) Experimental setup of the LSC "homemade" characterization; b) comparison between the performance of the isomalt-curcumin LSC with three different characterization techniques (PV cells, photodiode, smartphone illumination sensor). Error bars are confidence intervals (α = 0.05) after measuring every edge of the devices.

(η_{dev}), obtained by connecting two PV cells to the edge of the LSC and measuring the electrical power extracted from them ($P_{el\ out}$) versus the luminous power hitting the top surface of the LSC ($P_{opt\ in}$). η_{dev} assesses the LSC performances in the light-to-electricity conversion (Figure 3b). For this system, it reached a maximum value of 0.65, lower than other state-of-the-art devices[46] and data gathered from our lab comprising PMMA-based LSC (~1−1.2),[31] but representative of the light collecting ability of the isomalt LSC devices and still comparable to other recently published devices that were not optimized for η_{dev}.[47] A complete characterization of photonic efficiencies is available in the SI (Figure S6). Although they would have no practical use, curcumin-isomalt LSCs displayed notable performance. This is particularly remarkable since they can be prepared in a kitchen at home employing all-edible ingredients available at the supermarket (see "Home experiment" section in the SI).

While these LSCs are, per se, a simple and interesting experiment to do, we used characterization procedures to evaluate their efficiencies which required specialized equipment. While we deemed this necessary to assess that isomalt-based LSC possess concentrating properties by following the recently released protocols,[24,25,48] such elaborate procedures hamper the simplicity of the experiment. To make the performance assessment more accessible, we explored other solutions based on more available materials and devices. For instance, inspired by an earlier work of ours,[27] we tested the possibility of using a photodiode to evaluate the light emitted from the edge of the LSCs. Photodiodes can be found at reasonable prices and require limited wiring to be implemented. Also, we decided to employ the white LED flashlight of a smartphone to illuminate the 3 × 3 × 0.2 cm^3 LSCs to avoid the use of a solar simulator (Figure S7). The input power density spectrum of the smartphone flashlight is shown in the SI document. The data measured for the series of curcumin-isomalt LSCs are reported in Figure 3b as the current ratio between the values measured with the LSC connected and without. As one can notice, even the pure isomalt slabs (0 wt % samples) show efficiency values above zero since, even without a fluorophore, some light can be trapped inside the slab and emitted from the edges. The data obtained this way agrees qualitatively with those obtained from the state-of-the-art characterization; however, the errors associated with the different points are quite large and many differences cannot be considered statistically relevant. In pursuit of other simple and available methods that could be employed to estimate the LSC performances, we decided to test the illumination sensor present virtually on every smartphone nowadays. In particular, with apps such as Phyphox,[49] it is possible to exploit the light sensor of a smartphone as a detector to monitor light intensity (in lux). Unfortunately, although available both on Google Play and the App Store, the app does not have access to the light sensor on an iOS devices. The authors suggest using the photodiodes method mentioned above as alternative. It is worth mentioning that photodiodes and these smartphone light sensors are not reliable in the case of quantitative measurements;[50] however, for relative and qualitative comparisons, their performances suffice. In our case, this approach was used to acquire the edge-emitted illuminance of the LSCs (Figure 3a). We employed another smartphone for the illumination, so that, in principle, anyone can repeat the same protocol as long as they have two smartphones and an app that can access the illumination sensor of one of them. Alternatively, sunlight entering from a window is also a viable source.

Real-time data were collected on each side of the devices so as to calculate an average illuminance at each fluorophore concentration. The whole characterization of a set of LSCs can be carried out in 5 min, a surprisingly short amount of time compared to the characterization protocols. Not all LSC edges have the same light concentration (Figure S8), since the uneven thickness and the presence of bubbles limit the homogeneity of the devices.

Results are finally expressed as the illuminance ratio, obtained dividing the average illuminance obtained with an LSC at one concentration by the illuminance acquired without the LSC (Figure 3).

In the case of all the techniques employed, a noticeable increase in performance is seen in the 0.001−0.01 wt % range, with the achievement of a plateau-like trend for higher concentrations. In fact, a further increasing of concentration led to the formation of low-emissive curcumin aggregates (Figure S9). Notably, the error bars associated with this latter method are smaller than those obtained with the photodiode. Although the smartphone illumination sensor cannot distinguish and count photons of different wavelength separately, we observed a good agreement with η_{dev}. The EQE of the PV cells mounted on the edges is almost constant from 400 to 1000 nm (Figure 1b), thus the current produced by the cells can be considered directly proportional to the intensity of the edge-emitted light.[36] Hence, a cost-effective and omnipresent tool such as a smartphone can effectively provide relative light-collecting efficiencies of LSC when a high level of accuracy is not required.

The educational advantage of this performance evaluation lies in concretizing the LSC working principles. In fact, a simple classroom exercise could, with a rough conversion between the illuminance ratio and device efficiency given by this work, lead students to calculate a hypothetical energy output, and assess whether it was sufficient to power a simple electrical device such as a light bulb.

The experience described in this manuscript was tested in an educational setting with high-school students (17−18 years old) and in a house experiment with kids (10−13 years old). Remarkably, in the case of the high school students, the data they collected on the LSCs they fabricated were directly comparable to those obtained by the authors during the preparation of this manuscript (Figure S10). The opinion of the students about this experience was evaluated through a questionnaire (Figure S11). The reader can find more information about these experiences in the SI.

CONCLUSIONS

In this work, we developed a visually appealing and minimum-risk experiment that can be used to discuss the topics of fluorescence and solar energy harvesting, highlighting the role that chemistry and materials can play in the energy transition and toward the reach of the sustainability goals. In particular, we fabricated and characterized functioning LSC devices employing readily available common food materials such as isomalt and curcumin or riboflavin as fluorophores. Remarkably, the device can be fabricated in a regular kitchen without any technical equipment. Despite being fabricated from edible materials, we could easily assess the device efficiency with a reasonable degree of accuracy and, for isomalt-curcumin mixtures, found it to be comparable with other LSCs in the literature, i.e., max η_{dev} of 0.65% compared to values around 1−1.2 in case of other reported systems.

In addition, we showed that it is possible to qualitatively characterize their performances by using available setups such as smartphones, which can serve as light source and detector, or photodiodes. For example, in the potential setting of a high school classroom, every student would be able to perform both the LSC fabrication and their (rapid) characterization, as long as they have a smartphone.

Students can explore concepts such as light absorption and fluorescence, reflection, and refraction by experiencing a practical application. In particular, this demonstration can allow them to critically investigate the different parameters used to describe the absorption and emission properties of a fluorophore-matrix system and relate those to a practical application. Teachers and science demonstrators at large can use this experiment to make photovoltaics more understandable and exemplify the potential of chemistry and materials science for photovoltaics technologies and the energy transition.

Notably, one can set up this demonstration in a home setting to engage younger kids and introduce them to the fascinating world of fluorescence and unusual optical phenomena.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.3c00709.

Additional experimental details, materials, and methods, including photographs of experimental setup (PDF)

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This research is supported by the Ministry of University and Research (MUR) as part of the PON 2014-2020 “Research and Innovation” resources−Green/Innovation Action−DM MUR 1061/2022.

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