Performance Comparison of Fast, Transparent, and Biotic Heaters Based on Leaf Skeletons

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Bioinspired, highly flexible, fast, and biodegradable heaters are fabricated based on Ag nanowires and leaf skeletons of different plant species. The leaf skeletons act as transparent substrates with a high surface-area-to-volume ratio and allow a uniform dispersion of the Ag nanowires through the surface. Ag nanowires adhered to the leaf skeletons display very good transmittance (up to ≈87%) and mechanical (flexibility) properties (curvature values >800 m⁻¹) without any post-treatment. The flexible leaf skeleton-based heaters reach high temperatures very quickly, with very low voltages (<4 V). The performance of the bioinspired heater surface is dependent on the types of fractal structures at the microscale. The morphology of the leaf skeletons is studied in detail and is correlated with the transmittance, flexibility, and sheet resistances. Bioinspired heater surfaces based on different leaf skeletons are compared based on their multiscale morphology, and the different heating performance parameters are screened. Based on the study conducted, insights on the best-performing biotic design for the fabrication of the heaters that are useful in practical wearable, medical, or industrial heating applications are provided.

1. Introduction

The advancement of the design and fabrication of transparent film heaters has gained attention in recent times due to their application in panel displays,[1] defrosters,[2] sensors,[3] and devices of industrial importance.[1,2,4] Currently, most of the reports in their design are directed toward wearable electronics, next-generation textiles, and flexible biomedical devices such as thermotherapy patches.[5–10] The thermotherapy patches improve blood circulation, stop inflammation, ease pain, and are very effective in the treatment of various types of arthritis.[11] For this application, optical transparency and portability, flexibility, fast response, breathability, and uniform heating are also important.[6,12] Various types of conducting polymers,[4] semiconductor oxides,[13] their composites, and most recently carbon-based nanomaterials[14,15] have been proposed for flexible thermotherapy patches due to their flexibility, transparency, and good electrical conductivity. However, most of the heater surfaces are not very promising during different types of mechanical strains that occur during bending and folding. In addition, the surfaces require high voltages to reach the operating temperatures that limit their usage in thermotherapy patches.[1,3,7] In almost all the reports, the intrinsic and extrinsic mechanical and electrical properties of the materials take focus to improve the overall performance of the heater surfaces.

As an alternative, metallic nanowires have been developed to provide excellent transmittance and conductance and thus have been brought forward as a potential candidate for transparent electrical conductors in thin-film flexible electronic devices.[16,17] In current times, the silver (Ag) nanowire network is the most explored conductive material for the fabrication of transparent electrodes and their applications due to its excellent conductivity, optical transparency in the visible region, and excellent flexibility.[18] However, an increase in the concentration of the Ag nanowires on the substrate decreases the sheet resistance and reduces the transmittance drastically.[19] This is because the increase in Ag nanowires concentration makes the layer thick, which hinders any light to pass through it. A random nanocrack network of Ag nanowires has been reported, where transparency of the surfaces can be maintained by bundling nanowires in a micro-mesh-like network.[20] Apart from Ag nanowires, Cu nanowires have been recently reported, which may provide a cost-effective alternative to Ag nanowires.[21–24] The arrangement of the nanowires in bundles or close contact with each other is also important for such applications. This is because metal nanowire-based networks sometimes display large junction resistance between nanowires and require annealing techniques such as regular thermal annealing, laser nanowelding, flash lamp welding, chemical-assisted joining, mechanical welding, etc.[25–28] The substrates used for these purposes are mostly polymers such as polyethylene naphthalate, polyethylene terephthalate, polyimide, etc.[1,3,4,30,31] These polymers have high thermal resistance that leads to low thermal efficiency, slow thermal response, and high input voltages. Apart from engineering the intrinsic properties of the material, the architecture of the films at the micro- and
nаноуровень также играет важную роль в максимизации эффективности Ag-нанопроводников на основе плёнок.

Биоинспирированные поверхности с особенностями функциональности привлекают внимание в области исследований в реальных условиях. Эти структуры и механизмы, которые формируют функциональные биологические поверхности с интересными свойствами, привлекли внимание инженеров. Источники на интеграции биотических структур и материалных свойств, а также использование различных традиционных методов производства. Многие биоинспирированные архитектуры и фрактальные структуры, которые появляются при разных масштабах и фрактальных структурах, могут быть найдены в природе. Фрактальные структуры видны в разных местах, например, на листьях и венцах, и могут быть использованы на разных масштабных уровнях. Фрактальные структуры, которые обеспечивают высокое покрытие поверхности, улучшают стабильность, и эффективное транспортирование ионов, которые были отмечены.

Фрактальные структуры также способствуют улучшению тепловой эффективности. В предыдущей работе мы продемонстрировали, что скелеты листьев имеют преимущество при увеличении поверхности-объёмного отношения, что обеспечивает улучшение тепловой эффективности. Фрактальные структуры позволяют собирать электрическую и тепловую энергию и благоприятно влияют на улучшение работы скелета листьев и высокую поверхность фрактальных структур.

Функциональные устройства, инспирированные природой, могут быть использованы в различных областях. С его помощью, мы можем оценить оптическую прозрачность фрактальных структур. В конечном итоге, мы можем использоано фрактальные структуры, которые позволяют улучшить работу скелета листьев и создать эффективные узоры. Фрактальные структуры также способствуют улучшению работы скелета листьев и способствуют улучшению работы скелета листьев и расширению использования этих структур.

2. Results and Discussions

Процесс изготовления скелета листьев описан в экспериментальном разделе и схематически изображен на Рисунке 1а. Для изготовления биоинспирированных электрических узлов, листья, которые принадлежат к различным растениям, были выбраны на основании их формы и видимой прозрачности. В случае листьев, у которых нет значительных изменений в прозрачности, мы можем использовать их для разных областей гибких электроник.

Вариации в ориентации листьев и формы являются результатом адаптации разных видов растений.
skeletons and, barring *Q. velutina*, the Ag-coated leaf skeletons only displayed 6 percentage points or less decrease in the overall values (Figure 1c).

The scanning electron micrographs of the leaf skeletons coated with Ag nanowires are shown in Figure 2. The images clearly show that there is an architectural difference between the fractal structures of different leaf skeletons. Figure S1, Supporting Information, shows further magnified scanning electron microscope (SEM) images that show the significant difference in the bundles of vessels and interconnected fibers. Cell blocks in some of the skeletons are short, as evident from Figure S1, Supporting Information, while some show the long continuous bundles, as summarized in Table 1. The fractals of the different leaf skeletons have different arrangements of fiber interconnections and the distances range from a few micrometers to a few hundred micrometers. The distances are calculated based on the SEM images and are summarized in Table 1. Figure S2, Supporting Information, shows the arrangement of the Ag nanowires after they adhered to the leaf skeletons. The Ag nanowires used in the study have an average aspect ratio of ≈1000 and, as evident from the SEM images, the nanowires uniformly adhere to the surface. There are numerous micropores on the skeletons that soak the Ag nanowire dispersion liquid (water), leaving nanowires on the surface (Video V1, Supporting Information). The arrangement of the nanowires shows a continuous network that spreads across the leaf skeleton surface.

The optical, mechanical, and heating properties depend on the morphology of the fractals at the microscale. To investigate the fractal orientation and the fractal morphology, the total area covered by the skeletons was also calculated using ImageJ software. From the data, *Q. velutina* and *E. aureum* had the maximum area coverage with 89±4% and 63±12%, respectively. As shown in Figure 3a, most of the leaf skeletons had average surface coverage in the range of 40–60%. The skeletons of *M. sieboldii* had the lowest average surface coverage of 39±10% with some samples even showing coverage of 35%. The skeletons based on *L. lucidum* also had low area coverage with some samples showing the fractal coverage of 39%. However, the network, in this case, was not as dense as observed in the other skeletons. The values obtained from the surface area coverage also correlate well with the transmittance values, as shown in Figure 1b,c. Hence, lesser surface area coverage tends to increase the transparency of the leaf skeletons.

Fractal analysis is generally used to describe the complexity of plant structures. Fractal dimension is a value that can account for how a fractal pattern changes with the scale at which it is measured. It can be also used to measure how a fractal pattern scales differently from the topological space it is embedded and can be used to complement the area coverage or space filling of the microstructures.[40] To further gain insight regarding the surface morphology of the leaf skeletons, dimensions of the fractals (FD) were calculated using the box-counting method in...
ImageJ. The results of the fractal dimension calculations for the leaf skeletons are summarized in Table 1. As evident from the data, the FD of almost all the leaf skeletons ranged between 1.5 and 1.8, which is typical for the leaf skeletons reported in the literature. The skeletons based on *B. blakeana* showed the highest FD value of 1.721 followed by *F. microcarpa* (1.718) and *E. aureum* (1.708). The values also correspond well with the SEM images that show a very dense network of fractals. As expected, the skeletons of *M. sieboldii* (1.589) had FD in a slightly lower range that is also in agreement with the SEM data where a less dense network is evident.

To compare the effect of the fractal architecture on the conductivity, we loaded Ag nanowires onto the surface using the procedure detailed in the Experimental Section. This loading concentration of the nanowires was kept the same.
in all the samples and sheet resistance was measured. Except for Q. velutina, all the skeleton-based electrodes displayed uniform sheet resistance values that were less than 10 Ω sq^{-1}, as shown in the inset of Figure 3b. Conductive leaf skeletons based on Q. velutina displayed comparatively higher resistances > 50 Ω sq^{-1} that could be because of a very limited gap between the interconnected fibers and more area coverage (refer to Figure 2). This arrangement would require a greater number of nanowires that usually is reported in the planar thin-film heater surfaces. The fractal structures having thinner fractal dimensions (<100 μm) and area coverage less than ≈60% displayed the average sheet resistance lesser than 10 Ω sq^{-1}. The surfaces based on P. tremuloides displayed the lowest sheet resistance. However, if the area coverage and corresponding resistances are taken into consideration, M. sieboldii-based surfaces displayed the lowest sheet resistances and area coverage, as shown in Figure 3b.

To gain further insight into how the different leaves compare in terms of their conductivity and transparency, we calculated two different figures of merit (FOM) for the different leaves using equations

\[ \Phi_{TC} = \frac{T^n}{R_s} \]  

Table 1. Morphology observations of leaf skeletons.

| S.No. | Leaf skeleton | Fiber interconnection gap [μm] | Cell blocks [length in μm] | Fractal dimensions [FD] |
|-------|--------------|-------------------------------|---------------------------|-------------------------|
| 1     | P. tremuloides | ≈80–100 | Short (≈5–15) | 1.681 ± 0.001 |
| 2     | B. blakeana   | ≈50   | Short (≈5–15) | 1.721 ± 0.001 |
| 3     | F. microcarpa | ≈20–30 | Short (≈5–20) | 1.718 ± 0.01 |
| 4     | L. lucidum    | ≈200–500 | Long (>90) | 1.631 ± 0.002 |
| 5     | M. sieboldii  | ≈100–300 | Long (>50) | 1.589 ± 0.013 |
| 6     | E. aureum     | ≈50–100 | Medium–Long (≈20–100) | 1.708 ± 0.001 |
| 7     | Q. velutina   | –     | – | – |
| 8     | H. brasiliensis | ≈50–200 | Short (≈5–50) | 1.674 ± 0.029 |

Figure 3. Conducting surfaces characterization: a) percentage (%) area covered by the fractals and b) sheet resistance of the different skeleton surfaces with fixed Ag nanowires loading (≈160 μg cm^{-2}) plotted against the area coverage. The inset shows the sheet resistance corresponding to different Ag nanowire-covered leaf skeletons. c) FOM (Φ_{TC}) values corresponding to different leaf skeletons d) show the resistance values of different Ag-loaded leaf skeletons plotted against their corresponding curvatures.
\[ \Phi_M = -\frac{1}{R_s \log T} \]  

(2)

where \( T \) is the average transmittance value in the visible range, \( R_s \) is the sheet resistance, and \( n \) is a parameter that adjusts how the FOM weighs transmittance relative to sheet resistance in Equation (1).\(^{[44]}\) Equation (1) was proposed by Haacke,\(^{[44]}\) who studied how the FOM ranks different surfaces when \( n = 1 \) or \( n = 10 \): here, we used \( n = 10 \). We derived \( \Phi_M \) (eq. 2) from \( \Phi_{TC} \) (Equation (1)) using the following reasoning: for surfaces that follow Beer–Lamberts law

\[ T = \exp(-\alpha t) \]  

(3)

where \( \alpha \) is the optical absorption coefficient and \( t \) is the thickness.\(^{[44]}\) At the same time, the sheet resistance

\[ R_s = \rho / t \]  

(4)

where \( \rho \) is the electrical resistivity of the material. Even if leaf surfaces cannot be thinned beyond their normal thickness, many layers of leaves can be stacked on top of each other, giving \( T = T^k \) or \( k = \log(T) / \log(T) \), and \( R_s = R_s / k \), where \( \log(T) \) and \( \log(R_s) \) are the transmittance and sheet resistance after stacking multiple samples on top of each other. If for every sample enough layers would be stacked until they have the same transmittance \( T \), then

\[ \Phi_{TC} = \frac{T^2}{R_s} = \frac{T^2}{R_s \log(T) / \log(T)} \sim -\frac{1}{R_s \log T} = \Phi_M \], given that \( T \) was the same for all stacks of leaves. The minus sign was kept having larger values, indicating better surfaces for both FOM. To summarize, \( \Phi_M \) ranks the surfaces the same as \( \Phi_{TC} \), provided that the thickness of each sample is adjusted so that each sample has the same transmittance. Furthermore, plugging in (3) and (4) into (2), we have

\[ \Phi_M = \frac{1}{\rho \alpha t} \]  

(5)

which further shows that \( \Phi_M \) is independent of the thickness and only dependent on the intrinsic material properties.

The calculated results based on the new FOM are given in Figure 3c. The heater surfaces based on \( P. \) tremuloides with \( \approx 160 \) \( \mu \)g cm\(^{-2} \) had the best \( \Phi_M \) value of 3.324 \( \Omega^{-1} \) \((T = 88\%), \ R_s = 4 \Omega \) sq \(^{-1} \), representing good agreement between \( R_s \) and \( T \). Heater surfaces based on \( M. sieboldii \) closely followed with \( \Phi_M \) value of 2.792 \( \Omega^{-1} \) \((T = 88\%), \ R_s = 6.4 \Omega \) sq \(^{-1} \). Such conducting surfaces applied for the transparent heater are expected to meet the requirements of maintaining visually high transmittance and low reflectance not only when used as thermotherapy patches, but also for other applications. The new FOM values calculated also correspond well to the ones proposed by Haacke,\(^{[44]}\) where heater surfaces based on \( P. \) tremuloides and \( M. sieboldii \) show the highest FOM values of \( \Phi_{TC} = 0.0442 \) and 0.0432 \( \Omega^{-1} \), respectively (Figure S3, Supporting Information).

If the conducting surfaces are to be used in flexible electronics applications, these should be flexible, without plastic deformation or cracking. To compare the flexibility of the different leaf skeletons, the surfaces were clamped from their edges and bent with the help of a linear translation stage. The curvature of the leaf and the resistance of the electrodes were recorded during this process and the results are shown in Figure 3d. The plot also shows the maximum curvature values until the leaves were snapped. As expected, the resistances of the surfaces did not change much and that can be credited to the high aspect ratio and conformal attachment of the Ag nanowires. However, as evident in the figure, there was a significant difference in the maximum curvature values of the leaf skeletons of different species. The leaf skeletons based on \( P. \) tremuloides, \( B. blakeana \), \( F. macrocarpa \), and \( H. brasiliensis \) displayed the best flexibilities with curvature values exceeding 800 m\(^{-1} \). \( E. aureum \) and \( Q. velutina \) displayed the least flexibility, and the electrodes based on them snapped around the curvature of 200 m\(^{-1} \). Electrodes based on \( L. \) lucidum and \( M. sieboldii \) had slightly better flexibility, but the electrodes snapped before the curvature values of 400 and 600 m\(^{-1} \). As the leaf skeletons are made up of organic matter based on lignin, the difference in the flexibility can be correlated with the arrangement of the microstructures. Based on the SEM images displayed in Figure 2 and the curvature values, we observed that the skeletons that have small blocks of cells in their fracts are more flexible. The cell blocks with a longer orientation are more prone to snapping at the lower-curvature values.

When the Ag nanowire-coated leaf skeletons are used as heaters, various performance parameters are to be considered that are required in specific applications. Apart from the mechanical and optical parameters, other parameters include low operating voltages, fast response times, uniform heating across the surface, steady temperature, and good heating rates. The Joule heating characteristics of different leaf skeletons were studied for the \( \approx 160 \) \( \mu \)g cm\(^{-2} \) Ag nanowire density. For this, a continuous DC voltage was applied between the two edges of the heater having dimensions of 2 cm \( \times \) 2 cm and the heating properties were evaluated (details in the Experimental Section). Figure 4 shows the infrared images of the different leaf skeletons bearing a network of Ag nanowires when a bias of 2 V was applied. As evident from the images, almost all the skeleton-based electrodes show a rise in temperature throughout the surface. The infrared images shown in Figure 4 illustrate the uniformity of heating across the surfaces. This is also the indicator of the uniform distribution of the Ag nanowires across the surface. Upon comparison, the heater surfaces based on \( H. brasiliensis \) showed the most uniform heating throughout the surfaces even when bent (refer to Figure S4, Supporting Information). The electrodes based on \( M. sieboldii \) and \( B. blakeana \) also showed uniform heating on the surface that may be credited to the uniform distribution of the nanowires. The heaters based on \( E. aureum \) skeletons showed slightly uneven heat distribution. This may be due to the presence of uneven microstructures that are composed of medium-long cell blocks and might be responsible for uneven heat transfer. In addition, the skeleton-based heater surfaces are stable as well. A tape test was conducted on the heater surfaces based on \( H. brasiliensis \) as it showed most uniform heating (Figure S5, Supporting Information). A scotch tape (3M) was applied to the heater surface, pressed with a finger, and then peeled off after 5 s. Uniform heating on the surface was observed even after tape removal. The electrical tape (3M) was applied to the same surface and the process was repeated. The heater
surface was able to maintain uniform heating, proving that the Ag nanowires are still present on the surface and the surface is stable.

To compare the heating characteristics, the heater surfaces were subjected to different bias voltages (1 V increment) and the temperature was recorded until the heater failed (Figure 5a). The electrodes based on *F. macrocarpa* and *M. sieboldii* recorded average highest temperatures of $\approx 130^\circ\text{C}$ (3 V) and $\approx 139^\circ\text{C}$ (4 V), respectively, before failure. The electrodes based on *B. blakeana* (up to $\approx 128^\circ\text{C}$ at 4 V) and *H. brasiliensis* (up to $\approx 120^\circ\text{C}$ at 4 V) also displayed high temperatures with steady temperature increases. The heater surfaces based on *Q. velutina* and *E. aureum* displayed the lowest range of temperatures (max temperatures $\approx 55^\circ\text{C}$ at 8 V and $\approx 72^\circ\text{C}$ at 2 V). It is noteworthy to mention that with decreased loading of the Ag nanowires, the temperature ranges can be controlled, and the surfaces are stable for higher voltages as well.[6] The heater surfaces fail at various voltages and this may be due to very high local temperatures at some points, which may result in the breakage of the Ag nanowires.[19,45]

To compare the response time and reliability of the heater surfaces, their time-dependent temperature profiles were recorded. Figure 5b displays the time-dependent temperature profiles of heaters belonging to different leaf skeletons. For each heater, the Ag nanowire loading was kept fixed, and the temperature was recorded at 2 V. From the figure, the temperature increased almost instantaneously in all the heater surfaces and reached their corresponding operating temperatures within $\approx 15$ s. From the figure, it is also clear that almost all the skeleton-based heaters can maintain a steady-state temperature until the voltage is turned off. Rapid cooling was also observed in all the skeleton surfaces with the temperatures dropping immediately as soon as the voltage is turned off. For measurements of individual skeletons, three independent heater samples having the same Ag nanowire loading were tested at the same bias of 2 V, and the average values were taken into the consideration. However, the age, size, and shape of the leaf can lead to a slight variation in the orientation of the microstructures. This may also cause greater variations in the performance of the heater as well. Ag nanowires and leaf skeleton-based heaters show extremely fast response times, and this is one of the main virtues of transparent heater surfaces. This is because of the fast heat exchange, as reported in the study by Sharma et al.[6] Figure 5c shows the time taken by each heater surface to reach operating temperature. From the values, the skeletons based on *E. aureum* and *F. macrocarpa* were the fastest to reach the operating temperatures ($\approx 4.5$ and 5.5 s, respectively). Although almost all the heaters were very fast with most of the surfaces reaching the operating temperatures in less than 9 s. In comparison, only heaters based on *M. sieboldii* ($\approx 11$ s) and *B. blakeana* ($\approx 14$ s) took slightly more time to reach the operating temperatures. Based on the time taken to reach the operating temperatures, the rate constants for the heater surfaces were also calculated. Based on the data, the heaters based on *P. tremuloides* and *E. aureum* displayed the best rate constants with the average values of $\approx 4.4$ and $\approx 4.5$ °C s$^{-1}$, respectively. *Skelton-based* on *H. brasiliensis* also had very good heating rates with an average value of $\approx 3.7$ °C s$^{-1}$. In comparison, heaters based on *Q. velutina* skeletons displayed the lowest rate constant of $\approx 0.5$ °C s$^{-1}$.

Almost all the heater surfaces belonging to the leaf skeletons of different plant species displayed first-order dynamics and had very rapid heating and cooling. As expected, the heat transfer was directly related to the applied voltages, that is, higher voltages corresponding to higher temperatures. Like reported previously, the good heating profile and the quick response times are due to the lower thermal mass of the leaf skeletons (mostly composed of a porous network of the lignin and cellulose) in addition to the very high surface area provided by the fractal-like geometry.

There are three forms of heat transfer, convection, conduction, and radiation, and their energy balance can be expressed by

$$Q_{\text{total}} = Q_{\text{conduction}} + Q_{\text{convection}} + Q_{\text{radiation}}$$  \hspace{1cm} (6)

where $Q_{\text{total}}$ is the generated heat; $Q_{\text{conduction}}$ is the heat by thermal conduction, which can be neglected because the conduction losses are caused by external parts of the system.[3] $Q_{\text{convection}}$
Figure 5. a) Highest temperature of the bioinspired heater surfaces when the voltages are increased in 1 V increment until the heater fails. The Ag nanowires loading is $\approx 160 \mu g \text{cm}^{-2}$ on all the surfaces. b) Time-dependent surface temperatures of the heater surface having different fractal surfaces and same Ag nanowires loading ($\approx 160 \mu g \text{cm}^{-2}$ at 2 V). c) Time taken (s) by each heater surface to reach the operating voltage at 2 V and d) calculated rate constants of the surface to reach the operating temperature at 2 V. The error bars show the standard deviations calculated from three independent measurements. e,f) The relationship between the surface coverage to response times and rate constants, respectively.
is the convective heat loss in air; and \( Q_{\text{radiation}} \) is the radiative heat loss. As reported in the literature, \( Q_{\text{radiation}} \) is applicable only for high temperatures.\(^{112,46} \) This is because the radiative heat transfer coefficient of Ag with the lowest emissivity is small compared with the overall heat transfer coefficient. Hence, the heat in the skeleton-based heaters is mainly generated by convective heat in the air and the conductive heat when the power \( (P) \) is supplied to the surfaces based on Joule’s law.

\[
P = \frac{U^2}{R} = \epsilon \rho V \frac{dT}{dt} + hA(T - T_0) \tag{7}
\]

where \( \epsilon \) is specific heat capacity, \( \rho \) is the density, \( V \) is the volume of the surface, \( h \) is the heat transfer coefficient, \( A \) is the surface area, \( T \) is the surface temperature of the electrical heater, and \( T_0 \) is the temperature of the environment. Equation (7) is a first-order linear differential equation and has a time constant \( \tau = \frac{A}{c \rho h} \). Assuming that \( c, \rho, \) and \( h \) are approximately constants, the response time of the heater can be made faster simply by increasing its surface-to-volume ratio. Also, the steady-state temperature is given by

\[
T_{t \rightarrow \infty} = \frac{U^2}{RhA} + T_0 \tag{8}
\]

This means that an increase in the steady-state temperature and the heating power is proportional to the surface area, and this avoids the overheating of the heating element. Hence, the high surface area-to-volume ratio plays an important role in heating performance. Different leaf skeletons have different fractal structures and hence varying surface-to-volume ratios. Surface area coverages (refer to Figure 3a) serve as indicators that how much volume the fractals have covered. Lesser coverage means that the density of the Ag nanowires will be increased per unit area, leading to a decrease in the resistance. More surface coverage means that the surface-to-volume ratio is compromised that will have an impact on the response times and the temperature range. Although most of the leaf skeletons provide good surface coverage, high surface area, and minimum in-plane resistance, it would be worth predicting the best coverage range while designing devices.\(^{153,47} \) Figure 5e.f shows the relationship between the surface coverage to response times and rate constants, respectively. The heater surfaces based on \( E. \) aureum (surface coverage = \( \approx 63 \% \)) displayed the best performance in terms of response times and rate constants. Based on the data displayed in Figure 5e.f, it is safe to say that the good surface coverage range to design the heater is \( \approx 45 - 63 \% \). It is noteworthy to mention that the FD does not seem to have a direct impact on the heating characteristics of the surfaces.

Overall, the results reveal that the architecture of the leaf skeletons has a significant influence on the optical, mechanical, electrical, and thermal characteristics of Ag nanowires-coated leaf skeletons. The orientation and the arrangement of the structural lignin influence the flexibility and give insight toward the flexible surfaces. Surface area coverage, the gap between the fractals, and the fractal dimensions are also important parameters that influence the heating performances. Heater surfaces based on various skeletons excel at many individual parameters such as high optical transparency, high flexibility, stable and high operating temperatures, and very rapid response times. Based on the analysis, the heater surfaces based on \( H. \) brasiliensis performed well and displayed good transparency, flexibility, uniform heating, stable operating temperatures complemented by the rapid response times, and good rate constants.

3. Conclusion

In pursuit of an ideal biotic design for the fabrication of the heating patches for thermotherapy, we fabricated the heater surfaces based on leaf skeletons of different plant species. Ag nanowires were coated onto the skeleton surfaces to obtain heater surfaces. The optical transmittance, flexibility, and heating properties were studied in detail and were correlated with fractal architectures at the microscale. Based on the performance analysis, we conclude that the leaf skeletons based on \( H. \) brasiliensis provide overall a good substrate for fabricating heaters that could be directly utilized in thermotherapy applications. By testing individual heater surfaces belonging to different species, insights regarding the different heating parameters have been provided. The insights might be useful in the design of devices for different applications such as wearable electronics, medical applications, and industrial fields. To design and further improve the efficacy and performance of heater surfaces, one can derive inspiration from the hierarchical surface topography of the leaves in combination with advanced fabrication technologies.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

This work was supported by the Academy of Finland (grants: #331368, #299087, #292477, and #326461) and KONE foundation. All authors are grateful for the support from the Tampere Microscopy Center for the characterization of the surfaces.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Keywords

Ag nanowires, bioinspiration, leaf skeletons, transparent heaters

Received: November 25, 2021
Revised: December 23, 2021
Published online: January 22, 2022
